ENVIRONMENTAL SCIENCE IN BUILDING

R. McMullan

Environmental Science in Building

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Preface

This book studies the science of those services that contribute to the environment which exists in and around buildings. The main topics are heating, lighting and sound in buildings; and the supply of electricity and water to buildings. Although some subjects have to be introduced separately the text emphasises the necessity of an integrated approach to the study and design of environmental services.

The book is intended for students of building, civil engineering and surveying who are studying environmental science. The requirements of courses for degrees, for examinations of professional institutions, and for Technician Education Council awards should be satisfied by the contents of the book. It will also serve as a useful reference book for those in professional practice and for anyone interested in a knowledge of environmental science.

The motivation for the book stems from continuing teaching experience with many students and information is presented in a manner that has been found popular and successful. Topics are developed from basic principles and assume the minimum prior knowledge of science and mathematics. Important facts and formulae are highlighted in the text as an aid to reference and to memory. Definitions and units are introduced in a consistent form using recommended units and, where a numerical approach is relevant, worked examples are displayed step-by-step and supported by exercises for practice. The style of writing has been kept simple but, at the same time, it has a technical content and accuracy appropriate to this level of study. The text is illustrated by labelled drawings which are intended to help explain the text and to act as models for student sketches.

I wish to thank my colleagues and students who contributed, consciously or otherwise, to the book, and to give special thanks to Mrs A. McMullan who typed so much at such a distance.

R. McMULLAN

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Introduction

The topics in this book have been developed from fundamentals. The introductory section and the chapters on the basic principles of heat, light and sound will be of particular importance if little physics has been studied before. These parts of the book will also be useful to anyone needing revision.

For the *understanding* of a new topic the text should be read carefully; it has been written in a concise form. Appreciation of material in this book should also serve as preparation for the direct use of further technical sources. A reading list is given at the end of the book.

For quick *revision* and *reference* some information, such as definitions and formulae, has been highlighted in the text. Other information has been presented in lists which are intended to summarise the topics and to aid the memory. The items in a list should be regarded as starting points for more comprehensive discussions of the subjects.

Certain *calculations* are necessary for mastering some topics, and for passing examinations. The text emphasises those formulae which are especially useful and which may also need to be memorised. Important types of calculation are explained by carefully worked examples, using relatively simple calculations. Where further practice is relevant there are exercises at the end of the chapter.

The emphasis of the book, and of the courses and examinations with which it is associated, is to develop an understanding of the principles of environmental science. The text itself gives an indication of the depth of knowledge normally expected at this level of study. The style of writing has been kept simple but it uses correct terminology and units. As such it may act as an example for the type of response expected when it is necessary to display a knowledge of a topic. The diagrams are intended to help to explain the subjects in the book. The drawings have been kept relatively simple so that they can form the basis for sketches. It should be remembered that accurate labels are as important as the drawings.

SI UNITS

The result of measuring a physical quantity is expressed as a number, followed by a unit. For example: length AB = 15 metres. In general

Physical quantity = Number x Unit

The number expresses the ratio of the measured quantity to some agreed standard or unit. Different systems of units have arisen over the years, including Imperial units and metric units. A rational and coherent version of the metric system has been developed, called the Systême Internationale d'Unités, or SI.

SI units are intended for worldwide scientific, technical, and legal use. The units in this book are given in SI and reference to older units is made only where such units are still used in technical practice.

There are seven base units in the SI system, two supplementary units, and numerous derived units some of which are listed in the table of units. Derived units can be formed by combinations of base units; for example, the square metre. Some derived units are given new names; for example, the newton is a combination of the kilogram, the metre, and the second; the pascal is a combination of the newton and the square metre.

The symbols for SI units do not have plural form and are not followed by a full stop, except at the end of a sentence. The symbols for derived units may be written in index form or with a solidus (/). For example: m s^{-2} or m/s^2.

TABLE 0.1 *SI units*

Quantity	Symbol	SI Unit	Symbol
Base units			
length	l	metre	m
mass	m	kilogram	kg
time	t	second	s
electric current	I	ampere	A
thermodynamic temperature	T	kelvin	K
luminous intensity	I	candela	cd
amount of substance		mole	mol
Supplementary units			
plane angle	θ, ϕ	radian	rad
solid angle	Ω, ω	steradian	sr
Some derived units			
area	A	square metre	m^2
volume	V	cubic metre	m^3
density	ρ	kilogram per cubic metre	kg/m^3
velocity	v	metre per second	m/s
force	F	newton	N (kg m/s^2)
energy	E	joule	J (N m)
power	P	watt	W (J/s)
pressure	p	pascal	Pa (N/m^2)

SI prefixes

Multiplication factors are used to express large or small values of a unit. These multiples or sub-multiples are shown by a standard set of prefix names and symbols which can be placed before any SI unit.

TABLE 0.2 *SI prefixes*

Prefix	Symbol	Multiplication factor
tera	T	10^{12} = 1 000 000 000 000
giga	G	10^{9} = 1 000 000 000
mega	M	10^{6} = 1 000 000
kilo	k	10^{3} = 1 000
milli	m	10^{-3} = 0.001
micro	μ	10^{-6} = 0.000 001
nano	n	10^{-9} = 0.000 000 001
pico	p	10^{-12} = 0.000 000 000 0001

The standard prefixes and symbols can be placed before any SI unit, with the exception of the kilogram. Multiples should be chosen so that the numerical value is expressed as a number between 0.1 and 1000.

The Greek alphabet

The symbols for some quantities and units are taken from the Greek alphabet.

A	α	Alpha	N	ν	Nu
B	β	Beta	Ξ	ξ	Xi
Γ	γ	Gamma	O	o	Omicron
Δ	δ	Delta	Π	π	Pi
E	ϵ	Epsilon	P	ρ	Rho
Z	ζ	Zeta	Σ	σ	Sigma
H	η	Eta	T	τ	Tau
Θ	θ	Theta	Υ	υ	Upsilon
I	ι	Iota	Φ	ϕ	Phi
K	κ	Kappa	X	χ	Chi
Λ	λ	Lambda	Ψ	ψ	Psi
M	μ	Mu	Ω	ω	Omega

Mathematical symbols and formulae

Some common symbols and formulae follow

a^n	a raised to power n
$\sqrt{a}, a^{1/2}$	square root of a
$\log x$	common logarithm of x
π	$\approx 3.141\ 593$
πr^2	area of circle
$2\pi r$	circumference of circle
$\frac{4}{3}\pi r^3$	volume of sphere
$4\pi r^2$	surface area of sphere
$a^2 = b^2 + c^2$	theorem of Pythagoras

1 Principles of Heat

Heat and its associated effects are a major factor in the quality of the environment. Both human beings and their buildings respond to the heat that is around them; they also contribute to this heat.

A successful thermal environment is usually the most important aspect in the good design and use of a building. Topics that are relevant to the design of the thermal environment include the requirements of human comfort, the types of heat loss and gain from buildings, and the nature of moisture in the air. Before these topics are considered this chapter explains the basic nature of heat, its measurement, and its effects. The nature of gases and their properties are also included in this chapter.

NATURE OF HEAT

Heat energy

The following modern definition of heat is a simple statement, but the idea of this statement was not obvious in the past and confused ideas about the nature of heat are still common.

Heat (*Q*) is a form of energy.

UNIT: joule (J). The same unit as for measuring any other form of energy. The joule is the standard SI unit of energy and should replace other units such as the following: calorie, where 1 cal = 4.187 J; kilowatt hour, where 1 kWh = 3.6 MJ; British Thermal Unit, where 1 BTU = 1.055 kJ.

Heat energy is an internal molecular property of a material. Other forms of energy include mechanical energy, electrical energy and chemical energy. These other forms of energy can all be converted to thermal energy. For example, the mechanical energy of moving surfaces is converted to heat by friction, electric currents flowing in conductors produce heat and burning converts the chemical energy contained in materials to heat.

Thermal energy often forms an intermediate stage in the production of other forms of energy. Most electrical energy, for example, is produced by means of the thermal energy released in the combustion of fuels. The thermal energy radiated from the Sun is also the origin of most energy used on Earth including the fossil fuels, such as coal and oil, which were originally forests grown in sunlight.

Power Power is a measure of the rate at which work is done, or at which energy is converted from one form to another.

$$\textbf{Power } (P) = \frac{\text{heat energy } (Q)}{\text{time } (t)}$$

UNIT: watt (W). By definition, 1 watt = 1 joule/second

The watt is often used in the measurement of thermal properties and it is useful to remember that it contains information about energy content *and* time.

Temperature

Temperature is *not* the same thing as heat. A red-hot spark, for example, is at a much higher temperature than a pot of boiling water; yet the water has a much higher heat 'content' than the spark.

TEMPERATURE is the condition of a body that determines whether heat shall flow from it.

Heat flows from objects at high temperature to objects at low temperature. When there is no net heat transfer between two objects they are at the same temperature.

Thermometers The human body is sensitive to temperature but it is unreliable for measuring temperature. The brain tends to judge temperature by the rate of heat flow in or out of the skin. So for example, a metal surface always 'feels' colder than a plastic surface even though a thermometer may show them to be at the same temperature.

A thermometer is an instrument that measures temperature by making use of some property of a material that changes in a regular manner with changes in temperature. Properties that are available include changes in size, changes in electrical properties such as resistance and changes in light emissions. Some of the more common types of thermometer are described below:

1. *Mercury-in-glass thermometers* These use the expansion of the liquid metal mercury inside a narrow glass tube. The mercury responds quickly to changes in temperature and can be used between –39 °C and 357 °C; the freezing point and boiling point of mercury respectively.
2. *Alcohol-in-glass thermometers* These use coloured alcohol as the liquid in the glass tube. Alcohol expands more than mercury and can be used between –112 °C and 78 °C, the freezing point and boiling point of alcohol respectively.
3. *Thermoelectric thermometers* These use the electric current generated in a

thermocouple, which is made by joining two different metals such as iron and constantan alloy. The current quickly varies with temperature and can be incorporated in remote or automatic control systems.

4. *Resistance thermometers* These use the change in electrical resistance which occurs when a metal changes temperature. Pure platinum is commonly used and the changes in its resistance can be measured very accurately by including the thermometer in an electrical circuit.
5. *Optical pyrometers* These measure high temperature by examining the brightness and colour of the light emitted from objects at high temperatures. The light varies with temperature and is compared with a light from a filament at a known temperature.

Temperature scales

In order to provide a thermometer with a scale of numbers two easily obtainable temperatures are chosen as upper and lower *fixed points*. The interval between these two points on the thermometer is then divided into equal parts, called degrees. The properties of water are used to define two common fixed points – the temperature at which ice just melts and the temperature of steam from boiling water – both measured at normal atmospheric pressure.

Celsius Scale The Celsius temperature scale numbers the temperature of the melting point of ice as 0, and the boiling point of water as 100.

CELSIUS TEMPERATURE (θ) is a point on a temperature scale defined by reference to the melting point of ice and the boiling point of water.

UNIT: degree Celsius (°C).

Degrees Celsius are also used to indicate the magnitude of a particular change in temperature, such as an increase of 20 °C. The less correct term 'centigrade' is also used instead of Celsius.

Thermodynamic Scale Considerations of energy content and measurement of the expansion of gases lead to the concept of an *absolute zero* of temperature. This is a temperature at which no more internal energy can be extracted from a body and it occurs at –273.16 °C. The absolute, or thermodynamic, temperature scale numbers this temperature as 0.

The other fixed point for the thermodynamic scale is the triple point of water – the temperature at which ice, water, and water vapour are in equilibrium (0.01 °C).

THERMODYNAMIC TEMPERATURE (T) is a point on a temperature scale defined by reference to absolute zero and to the triple point of water.

UNIT: kelvin (K).

The kelvin is the formal SI unit of temperature but the degree Celsius is also used in common practice. The interval of a kelvin is the same size as a degree Celsius, therefore a change in temperature of 1 K is the same as a change in temperature of 1 °C.

The general relationship between the two temperature scales is given by the formula

$$\boxed{T = \theta + 273}$$

where

T = Thermodynamic temperature (K)

θ = Celsius temperature (°C)

Heat capacity

The same mass of different materials can 'hold' different quantities of heat. Hence water must be supplied with more heat than the oil in order to produce the same rise in temperature. Water has a greater heat capacity than oil; a property that is not to be confused with other thermal properties such as conductivity.

The heat capacity of a particular material is measured by a value of specific heat capacity, and table 1.1 gives values for a variety of materials.

The SPECIFIC HEAT CAPACITY (c) of a material is the quantity of heat energy required to raise the temperature of 1 kg of that material by 1 °C.

UNIT: J/kg °C.

TABLE 1.1 *Specific heat capacities*

Material*	Specific heat capacity J/kg °C
Water	4190
Concrete and brickwork	3300
Ice	2100
Paraffin oil	2100
Wood	1700
Aluminium	910
Marble	880
Glass	700
Steel	450
Copper	390

* The values for particular building materials vary.

The heat capacity of water is higher than the heat capacities of most other substances, so water is a good medium for storing heat. The temperatures on the planet Earth are stabilised by the huge quantities of heat energy stored in the oceans and the presence of this water around islands, such as the British Isles, prevents seasonal extremes of temperature. In summer the water absorbs heat and helps to prevent air temperatures rising; in winter the heat stored in the water is available to help prevent temperatures falling. Heat exchange devices, such as boilers and heating pipes, also make use of the high heat capacity of water for transferring heat from one place to another.

Density The heat capacities of different materials are compared on the basis of equal masses. However, the same mass of different materials may occupy different volumes of space, depending upon their densities.

$$\textbf{Density } (\rho) = \frac{\text{Mass } (m)}{\text{Volume } (V)}$$

UNIT: kilogram per cubic metre (kg/m^3).

Heavyweight masonry materials, such as brick, concrete, and stone, have high densities. This means that relatively small volumes of these materials have a large mass and therefore provide a relatively high heat capacity in a small volume. An electric storage heater, for example, contains bricks which are heated by cheap-rate electricity and hold this heat for use later in the day. The heat storage provided by the bricks, concrete, and stone used in construction is particularly relevant to the thermal behaviour of buildings, as discussed in later chapters.

Change of state

All matter is made from small particles called atoms and for most materials the smallest particle that exists independently is a group of atoms which are combined to form a *molecule*. The spacing of the molecules in a substance and the forces between them determine the phase, or state of matter, of that substance.

In the normal ranges of temperature and pressure there are three possible *states of matter* and they have the following basic characteristics:

1. *Solid state* The molecules are held together in fixed positions; the volume and shape are fixed.
2. *Liquid state* The molecules are held together but have freedom of movement; the volume is fixed but the shape is not fixed.
3. *Gas state* The molecules move rapidly and have complete freedom; the volume and shape are not fixed.

The state of a substance depends upon the conditions of temperature and pressure which act on the substance. Consider, for example, the common forms of iron, water and oxygen. At certain temperatures a material will undergo a change of state and in this change its energy content is increased or decreased.

The absorption of heat by a solid or a liquid can produce the following changes of state:

$$\text{SOLID} \xrightarrow[\text{(Melting)}]{\text{Liquefaction}} \text{LIQUID} \xrightarrow[\text{(Boiling, Evaporation)}]{\text{Vaporisation}} \text{GAS}$$

The release of heat from a gas or a liquid can produce the following changes of state:

$$\text{GAS} \xrightarrow{\text{Condensation}} \text{LIQUID} \xrightarrow[\text{(Fusion)}]{\text{Solidification}} \text{SOLID}$$

Sensible and latent heat

In order to understand how most substances behave it is useful to consider the changes of state for water. Figure 1.1 shows the effects of supplying heat energy at a constant rate to a fixed mass of ice. When the sample exists entirely in a single state of ice, water, or steam the temperature rises uniformly as heat is supplied. This heat is termed 'sensible' because it is apparent to the senses.

SENSIBLE HEAT is the heat energy absorbed or released from a substance during a change in temperature.

When the sample is changing from one state to another the temperature remains constant, even though heat is being supplied. This heat is termed 'latent' because it seems to be hidden.

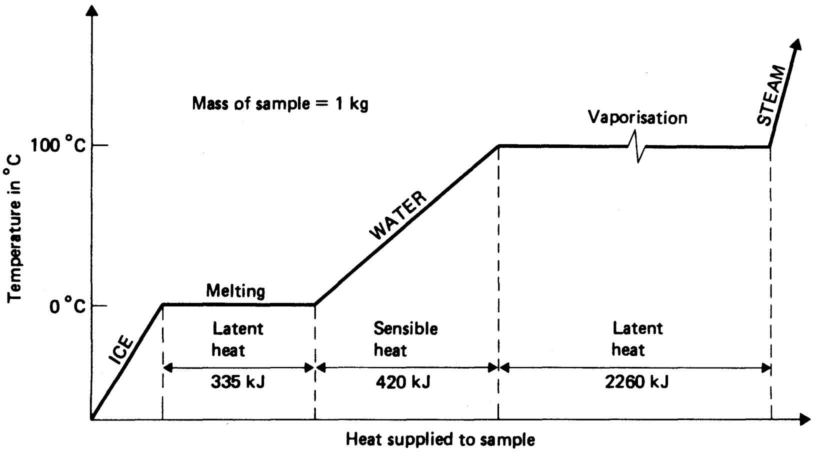


FIGURE 1.1 *Changes of state for water*

LATENT HEAT is the heat energy absorbed or released from a substance during a change of state, with no change in temperature.

The latent heat absorbed by melting ice or by boiling water is energy which does work in overcoming the bonds between molecules. It is a less obvious, but very important, fact that this same latent heat is given back when the steam changes to water, or the water changes to ice. The latent heat changes occur for any substance and have the following general names:

$$\text{SOLID} \xrightarrow[\text{absorbed}]{\text{Latent heat of fusion}} \text{LIQUID} \xrightarrow[\text{absorbed}]{\text{Latent heat of vaporisation}} \text{GAS}$$

$$\text{GAS} \xrightarrow[\text{released}]{\text{Latent heat of vaporisation}} \text{LIQUID} \xrightarrow[\text{released}]{\text{Latent heat of fusion}} \text{SOLID}$$

A liquid may change to a gas without heat being supplied, by evaporation for example. The latent heat required for this change is then taken from the surroundings and produces an important cooling effect.

Enthalpy is the total heat content of a sample, with reference to 0 °C. For the particular example of water shown in figure 1.1, the steam at 100 °C has a much higher total heat content than liquid water at 100 °C. Steam at high temperature and pressure has a very high enthalpy, which makes it useful for transferring large amounts of energy such as from a boiler to a turbine. This steam is also very dangerous if it escapes.

Calculation of heat quantities

Both sensible and latent heat are forms of heat energy that are measured in joules, although they are calculated in different ways.

Sensible Heat When a substance changes temperature the amount of sensible heat absorbed or released is given by the formula

$$\boxed{Q = mc\theta}$$

where

Q = quantity of sensible heat (J)

m = mass of substance (kg)

c = specific heat capacity of that substance (J/kg °C)

$\theta = \theta_2 - \theta_1$ = temperature *change* (°C)

* * * * *

Worked example 1.1

A storage heater contains concrete blocks with total dimensions of 800 mm by 500 mm by 220 mm. The concrete has a density of 2400 kg/m^3 and a specific heat capacity of 3300 J/kg °C. Ignoring heat losses, calculate the quantity of heat required to raise the temperature of the blocks from 15 °C to 35 °C.

$$\text{Volume} = 0.8 \times 0.5 \times 0.22 = 0.088 \text{ m}^3$$

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

so

$$\text{mass} = \text{density} \times \text{volume}$$

$$m = 2400 \times 0.088 = 211.2 \text{ kg}$$

Using $Q = mc(\theta_2 - \theta_1)$

$$= 211.2 \times 3300 \times (35 - 15)$$

$$= 13\,939\,200 \text{ J}$$

Quantity $= \mathbf{13.94\ MJ}$

* * * * *

Latent Heat During a change of state in a substance the amount of latent heat absorbed or released is given by the formula

$$\boxed{Q = ml}$$

where

Q = quantity of latent heat (J)

m = mass of substance (kg)

l = specific latent heat for that change of state (J/kg)

SPECIFIC LATENT HEAT (l) is a measure of the latent heat absorbed or released from a particular material for a given change of state.

UNIT: J/kg

Specific latent heat is sometimes termed specific enthalpy change and some common values are:

Specific latent heat of ice = 335 000 J/kg

= 335 kJ/kg

Specific latent heat of steam = 2260 000 K/kg

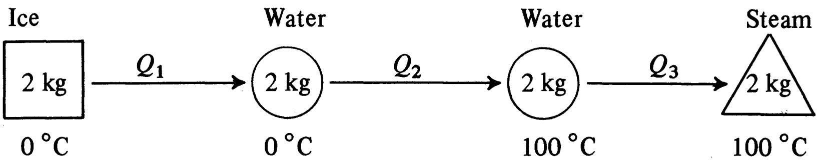
= 2260 kJ/kg

* * * * *

Worked example 1.2

Calculate the total heat energy required to convert 2 kg of ice at 0 °C completely to steam at 100 °C. The specific heat capacity of water is 4190 J/kg °C. The specific latent heats are 335 kJ/kg for ice and 2260 kJ/kg for steam.

Divide the process into sensible and latent heat changes:



(1) Changing ice at 0 °C to water at 0 °C requires latent heat.

Using $Q = ml$

$Q_1 = 2 \times 335\ 000 = 670\ 000$ J

$Q_1 = 670$ kJ

(2) Changing water at 0 °C to water at 100 °C requires sensible heat.

Using $Q = mc\theta$

$Q_2 = 2 \times 4190 \times 100 = 838\ 000$ J

$Q_2 = 838$ kJ

(3) Changing water at 100 °C to steam at 100 °C requires latent heat.

Using $Q = ml$

$Q_3 = 2 \times 2260\ 000 = 4520\ 000$ J

$Q_3 = 4520$ kJ

Total heat required = $Q_1 + Q_2 + Q_3$

= 670 + 838 + 4520

= **6028 kJ**

* * * * *

Expansion

Most substances expand on heating and contract on cooling. If the natural expansion and contraction of a body is restricted then very large forces may occur. Different substances expand by different amounts and the coefficient of linear thermal expansion is a measure of the relative change of length. Superficial (area) expansion and cubical (volumetric) expansion can be predicted from the linear expansion.

Solids The coefficient of linear expansion for steel is about $12 \times 10^{-6}/°C$, which means that a steel bar increases its length by 12/1 000 000 for each degree of temperature rise. Concrete expands at a similar rate to steel. The expansion of aluminium is about twice that of steel and the expansion of plastics is up to ten times that of steel.

Allowance must be made in constructions for the effects of expansion, particularly for concrete, metals and plastics. The result of destructive expansion can be seen in the twisted girders of a building after a fire. Expansion effects can also be useful. Heated rivets, for example, contract on cooling and tighten the joint between metal plates. The unequal expansion of two metals deforms a bi-metallic strip, which can then be used as a temperature switch like the thermostat shown in figure 1.2.

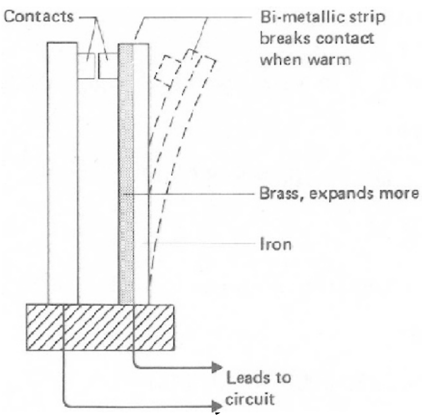


FIGURE 1.2 *Simple thermostat*

Liquids Liquids tend to expand more than solids, for the same temperature rise. The expansion rates of different liquids vary and the expansion of alcohol is about five times that of water. Most liquids contract upon cooling but water is unusual in that its volume increases as it cools from 4 °C to 0 °C. At 0 °C the volume of water expands by a larger amount as it changes to the solid state of ice.

Thermometers make use of the expansion of liquids but in the hot water systems of buildings and car engine blocks the expansion is troublesome if it is not allowed for. Rainwater that freezes and expands in the pores and crevices of concrete or stonework will disrupt and split the material. This process has, over long periods of time, destroyed whole mountain ranges.

Gases The expansion of gases is hundreds of times greater than the expansion of liquids. This will not be apparent if the gas is confined in a container because the pressure will then increase instead of the volume; this behaviour will be described in the later section on gases and vapours. If a gas is allowed to expand under conditions of constant pressure then the coefficient of volumetric expansion is found to be 1/273 per degree, starting at 0 °C.

The concept of an absolute zero of temperature at –273 °C was a result of imagining the effect of cooling an ideal gas. Starting at 0 °C, this ideal gas would shrink in size by 1/273 for each drop in temperature of 1 °C. At –273 °C the volume of the gas would therefore be zero, and matter would have disappeared. It is not possible to achieve this condition, although it is possible to approach close to it. Real gases do not actually stay in the gas state at very low temperatures, but the concept of an absolute zero of temperature remains valid.

HEAT TRANSFER

Heat energy always tends to transfer from high temperature to low temperature regions. There is no real thing as 'cold' that flows into warm places, even though the human senses may interpret the loss of heat energy as a 'cold flow'. If several bodies at different temperatures are close together then heat will be exchanged between them until they are at the same temperature. This equalising of temperature can occur by the three basic processes of heat transfer: conduction, convection and radiation. Heat may also be transferred by the process of evaporation when latent heat is absorbed by a vapour in one place and released elsewhere.

Conduction

If one end of a metal bar is placed in a fire then, although no part of the bar moves, the other end will become warm. Heat energy travels through the metal by the process of conduction.

CONDUCTION is the transfer of heat energy through a material without the molecules of the material changing their basic positions.

Conduction can occur in solids, liquids and gases although the speed at which it occurs will vary. At the place where a material is heated the molecules gain energy and this energy is transferred to neighbouring molecules which then become hotter. The transfer of energy may be achieved by the drift of *free electrons*, which can move from one atom to another, especially in metals. Conduction also occurs by vibrational waves called *phonons*, especially in non-metals.

Different materials conduct heat at different rates and the measurement of thermal conductivity is described in the next chapter. Metals are the best conductors of heat, because of the free electrons that they possess. Good conductors have many applications for the efficient transfer of heat, such as in boilers and heating panels.

Poor conductors are called insulators and include most liquids and gases. Porous materials that trap a lot of air tend to be good insulators and are of particular interest in controlling the heat flow through the fabric of buildings.

Convection

Air is a poor conductor of heat yet it is still possible to heat all the air in a room from a single heating panel – by the process of convection.

CONVECTION is the transfer of heat energy through a material by the bodily movement of particles.

Convection can occur in fluids – that is, liquids and gases – but never in solids. *Natural convection* occurs when a sample of fluid, such as air, is heated and so expands. The expanded air is less dense than the surrounding air and the cooler air displaces the warmer air causing it to rise. The new air is then heated and the process is repeated, giving rise to a 'convection current'.

Natural convection occurs in hot water storage tanks, which are heated by an electric element or heat exchanger coils near the bottom of the tank; convection currents ensure that all the water in the tank is heated. The term *stack effect* describes the natural convection that occurs in buildings causing warm air to flow from the lower to the upper stories. *Forced convection* uses a mechanical pump to achieve a faster flow of fluid, such as in the water cooling of a car engine or in a small-bore central heating system.

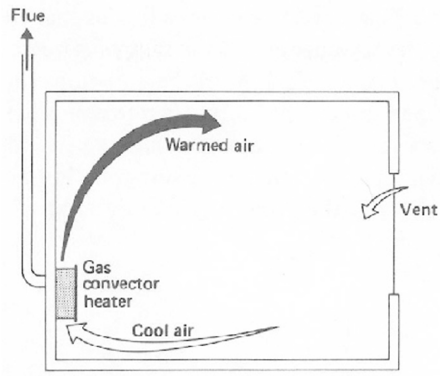


FIGURE 1.3 *Convection currents in room*

Radiation

Heat is transferred from the Sun to the Earth through space where conduction and convection is not possible. The process of radiation is responsible for this heat transfer through space and for many important effects on Earth.

RADIATION is the transfer of heat energy by electromagnetic waves.

Heat radiation occurs when the thermal energy of surface atoms in a material generates electromagnetic waves in the infra-red range of wavelengths. These waves belong to the large family of electromagnetic radiations, including light and radio waves, whose general properties are described in chapter 5.

The rate at which a body emits or absorbs radiant heat depends upon the nature and temperature of its surface. Rough surfaces present a larger total area and absorb or emit more heat than polished surfaces. Surfaces which appear dark, because they absorb most light, also absorb most heat. Good absorbers are also good emitters. Poor absorbers are also poor emitters. In general it is found that:

Dull black surfaces are the BEST absorbers and emitters of radiant heat.

Shiny silver surfaces are the POOREST absorbers and emitters of radiant heat.

These surface properties of radiation are employed for encouraging heat radiation as, for example, in a blackened solar energy collector. Or for discouraging heat radiation as, for example, by the use of aluminium foil insulation.

The rate at which a body emits heat increases with the temperature of the body. Every object is continuously emitting and absorbing heat to and from its surroundings. Prévost's Theory of Exchanges explains that the balance of these two processes determines whether or not the temperature of the object rises, falls, or stays the same. The wavelengths of the radiation emitted by a body also depend upon the temperature of the body. High temperature bodies emit a larger proportion of short wavelengths, which have a better penetration than longer wavelengths. The short wavelengths emitted by hot bodies also become visible at about 500 °C when they first appear as dull red.

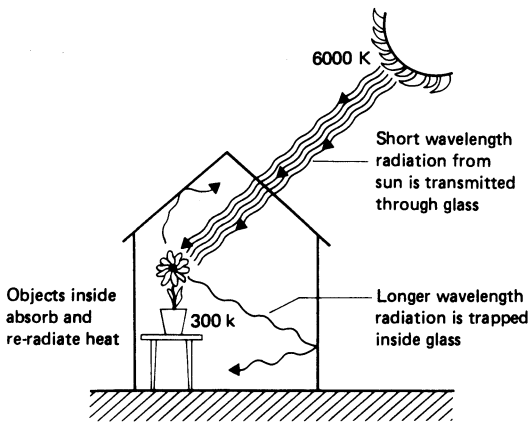


FIGURE 1.4 *Greenhouse effect*

The greenhouse effect, illustrated in figure 1.4, is a result of the different wavelengths emitted at different temperatures. The radiation emitted by the high-temperature Sun is of short wavelengths, which can pass through the atmosphere and through glass, and is then absorbed by plants or objects. These objects re-radiate the heat but, as they are at a lower temperature, the radiation is of longer wavelengths. These long wavelengths cannot penetrate glass or the atmosphere and so the heat is trapped.

GASES AND VAPOURS

Gases

The gas state is one of the three principal states in which all matter exists. According to the *Kinetic Theory*, the molecules of a gas are always in motion and their velocity increases with temperature. When the molecules are deflected by the walls of a container there will be a change in their momentum and a force imparted to the wall. The collisions of many molecules acting on a particular area will be detected as pressure.

$$\textbf{Pressure}\ (p) = \frac{\text{Force}\ (F)}{\text{Area}\ (A)}$$

UNIT: pascal (Pa) where, by definition: 1 pascal = 1 newton/metre^2 (1 N/m^2)

Gas laws

Heating a gas increases the velocity and the kinetic energy of the molecules. If the gas is free to expand then the heated molecules will move further apart and increase the volume of gas. If the volume is fixed the heated molecules will exert a greater force at each collision with the container and so the pressure of the gas increases. The gas laws are an expression of the relationships between the temperature, volume and pressure of a constant mass of gas.

Boyle's Law For a fixed mass of gas at constant temperature, the volume (V) is inversely proportional to the pressure (p).

$$pV = \text{constant} \quad \text{or} \quad p_1 V_1 = p_2 V_2$$

Charles' Law For a fixed mass of gas at constant pressure, the volume (V) is directly proportional to the thermodynamic temperature (T).

$$V = \text{constant} \times T$$

Pressure Law For a fixed mass of gas at constant volume, the pressure (p) is directly proportional to the thermodynamic temperature (T).

$$p = \text{constant} \times T$$

General Gas Law The relationships between the pressure, volume, and temperature of a gas can be combined into one expression

$$\frac{pV}{T} = \text{constant} \quad \text{or} \quad \frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

(Note: temperature must always be in kelvin.)

Dalton's Law of Partial Pressures Where there is a mixture of different gases each gas exerts an individual *partial pressure* and has the following features:

(1) The partial pressure exerted by each gas is independent of the pressure of the other gases.
(2) The total pressure of the mixture equals the sum of the partial pressures.

Standard Temperature and Pressure In order to compare gases measured under different conditions of temperature and pressure it is convenient to convert them to the following standard temperature and pressure (STP)

Standard temperature = 0 °C = 273 K

Standard pressure = 101.3 kPa
= 760 mm of mercury } 1 atmosphere

* * * * *

Worked example 1.3

At 20 °C temperature and 200 kPa pressure a certain sample of gas occupies a volume of 3 litres. What volume will this sample occupy at standard temperature and pressure?

Initial conditions: p_1 = 200 kPa, V_1 = 3 litres, T_1 = 283 + 20 = 293 K

Final conditions: p_2 = 101.3 kPa, V_2 = ?, T_2 = 273 K

Using $$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

$$\frac{200 \times 3}{293} = \frac{101.3 \times V_2}{273}$$

so

$$V_2 = \frac{200 \times 3 \times 273}{293 \times 101.3} = 5.519$$

Final volume = **5.519 litres**

* * * * *

Vapours

A vapour is a material in a special form of the gas state and has some different properties to those of a gas. For example, when a vapour is compressed the pressure increases until, at a certain point, the vapour condenses to a liquid.

A VAPOUR is a material in the gas state which can be liquefied by compression, without change in temperature.

The *critical temperature* of a substance is the temperature above which a vapour is *not* able to exist. Table 1.2 gives the critical temperatures of some

TABLE 1.2 *Critical temperatures*

Substance	Critical temperature (°C)
Oxygen (O_2)	– 119
Air	– 141
Carbon dioxide (CO_2)	31
Ammonia (NH_3)	132
Water (H_2O)	374

substances relevant to heating and refrigeration. So it is seen, for example, that steam is a vapour at 100 °C but a gas at 500 °C.

The atmosphere

Air is a mixture of gases and has the following percentage composition when it is clean and dry

Nitrogen (N_2)	78 per cent
Oxygen (O_2)	21 per cent
Carbon dioxide (CO_2) } Other gases }	1 per cent

The atmosphere is the collection of gases that surround the surface of the Earth. In addition to air the atmosphere contains up to several per cent of water vapour, and may contain local pollution products.

At the surface of the Earth the atmosphere produces a fluid pressure that depends upon the average density and the height of the atmosphere above that point. This pressure acts in all directions and varies with altitude and with local weather conditions. At sea level atmospheric pressure has a standard value of 101.3 kPa and is measured by barometers.

The *simple mercury barometer* consists of a glass tube sealed at one end which is filled with mercury and inserted upside down into a dish of mercury. A certain height of mercury remains in the tube, its weight balanced by the force resulting from atmospheric pressure. A standard atmosphere supports a 760 mm column of mercury and this height changes with changes in atmospheric pressure. The absolute unit of pressure is the pascal but it is also convenient to refer to pressure in terms of height, such as mm of mercury.

The *aneroid barometer* uses a partially evacuated box of thin metal whose sides move slightly with changes in atmospheric pressure. The movements are magnified by levers and shown by a pointer on a scale. Aneroid barometers are commonly used as altimeters and as household weather gauges.

EXERCISES

1 (a) Convert the following temperatures from degrees Celsius to degrees kelvin: 20 °C; 400 °C; −10 °C.
(b) Convert the following temperatures from degrees kelvin to degrees Celsius: 200 K; 300 K; 773 K.

2 Explain, using accurate terminology, the reasons for the following observations:
(a) The meat and gravy inside a hot pie burn the tongue more easily than the surrounding pastry, even though all parts of the pie are at the same temperature.
(b) A concrete floor feels colder to walk on than carpet, even though both are at the same temperature.

3 Calculate the total heat required to convert 2 kg of water at 60 °C completely to steam at 100 °C. (Given: the specific heat capacity of water is 4200 J/kg °C and the specific latent heat of steam is 2260 kJ/kg.)

4 An insulated hot water storage cylinder has internal dimensions of 0.6 m dia. and 1.5 m height. A heating element at the bottom of the cylinder supplies 74.81 MJ of heat to the water which is at an initial temperature of 8 °C. Ignoring any heat losses from the water and heat gains by the cylinder itself, calculate the following:
(a) the mass of water present in the cylinder;
(b) the temperature of the water after heating;
(c) the effective power of the heating element if the above temperature rise takes 4 hours.
(Given: density of water = 1000 kg/m^3; specific heat capacity of water = 4200 J/kg °C.)

5 Explain, with accurate reference to appropriate mechanisms of heat transfer, the following effects.
(a) The ability of a vacuum flask to keep liquids either hot or cold.
(b) The ability of silver paint on a roof to reduce heat loss from a building.

6 At standard temperature and pressure a certain sample of gas occupies 50 litres in volume. Calculate the pressure required to compress this sample to a volume of 20 litres while allowing the temperature to rise to 30 °C.

ANSWERS

1 (a) 293 K; 673 K; 263 K;
(b) −73 °C; 27 °C; 500 °C

3 4856 kJ

4 424.1 kg; 50 °C; 5195 W

6 281 kPa

2 Thermal Insulation

To maintain a constant temperature inside a building it is necessary to restrict the rate at which heat energy is exchanged with the surroundings. Keeping heat inside a building for as long as possible conserves energy and reduces heating costs.

Thermal insulation is the major factor in reducing the loss of heat from buildings. Adequate insulation should be a feature of good initial design but insulation can also be added to existing buildings. The relatively small cost of extra insulating materials is quickly paid for by the reduction in the size of the heating plant required and by the annual savings in the amount of fuel needed. These fuel savings continue throughout the life of the building.

One of the other benefits of good thermal insulation is that the risk of surface condensation is reduced because of the warmer internal surfaces. Good insulation can also reduce the time taken for a room to heat up to a comfortable temperature; as for example in a room that is unoccupied during the day.

It is useful to remember that good thermal insulation will also reduce the flow of heat *into* a building, when the temperature outside is greater than the temperature inside. In other words, a well-insulated structure will – if ventilation is controlled – stay cooler in the summer than a poorly insulated structure. In a large building this insulation will give savings in the energy needed to run the cooling plant.

INSULATING MATERIALS

A thermal insulator is a material which opposes the transfer of heat between areas at different temperatures. In present-day buildings the main method of heat transfer is by conduction, but the mechanisms of convection and radiation are also relevant.

Those materials that conduct heat least have their atoms spaced well apart; they will also tend to be porous and of low density. Gases have the most widely spaced atoms and are the best insulators against conduction. Air, which is a mixture of gases, is the basis of insulators such as aerated lightweight concrete, expanded plastics and cavities.

For air to act as an insulator it must be stationary, otherwise, if the air is allowed to move, it will transfer heat by convection. Construction methods that restrict the flow of air in and out of a building prevent convection – weather stripping of windows and doors for example.

Heat transfer by radiation is restricted by using surfaces that do not readily absorb or emit radiant heat. They reflect the electromagnetic waves of radiation, which behave like light waves, and the surfaces look shiny. An example of this type of insulator is aluminium foil, which is thin enough to make conduction negligible.

Types of insulator

Thermal insulators used in construction are made from a wide variety of raw materials and marketed under numerous trade names. They can be classified as the following general types:

1. Rigid pre-formed materials. *Example*: aerated concrete blocks.
2. Flexible materials. *Example*: fibreglass mats.
3. Loose fill materials. *Example*: expanded polystyrene granules.
4. Materials formed on site: *Example*: foamed polyurethane.
5. Reflective materials. *Example*: aluminium foil.

Properties of insulators

When choosing materials for the thermal insulation of buildings the physical properties of the material need to be considered. An aerated concrete block, for example, must be capable of carrying a load. The properties listed below are relevant to many situations, although different balances of these properties may be acceptable for different purposes.

1. suitable thermal insulation for the purpose;
2. suitable strength or rigidity;
3. resistance to moisture penetration;
4. resistance to fire;
5. resistance to pests and fungi;
6. compatibility with adjacent materials.

The measurement of thermal insulation is described in the following sections. As well as resisting the passage of moisture it is important that a material is able to regain its insulating properties after being made wet, perhaps during the construction of a building. The fire resistance of many plastic materials, such as ceiling tiles, is seriously altered by the use of some types of paints and manufacturers' instructions must be followed. Many bituminous products tend to attack plastics materials and this should be considered when installing the materials.

Thermal conductivity

In order to calculate heat transfer and to compare different materials it is necessary to quantify just how well a material conducts heat.

> **THERMAL CONDUCTIVITY (k) is a measure of the rate at which heat is conducted through a particular material under specified conditions.**
>
> UNIT: W/m °C

This coefficient of thermal conductivity, or 'k-value', is measured as the heat flow in watts across a thickness of 1 m for a temperature difference of 1 °C and a surface area of 1 m^2.

Different techniques of measurement are needed for different types of material. Referring to figure 2.1 the general formula is

$$\boxed{\frac{Q}{t} = \frac{kA(\theta_1 - \theta_2)}{d}}$$

where

k = thermal conductivity of that material (W/m °C)

Q/t = rate of heat flow between the faces (J/s = W)

A = cross-sectional area of the sample (m^2)

$\theta_1 - \theta_2$ = temperature difference between the faces (°C)

d = distance between the faces (m)

The thermal conductivities of some building materials are given in table 2.1. These values are a selection of measured values commonly used for standard calculations. It is important to remember that the thermal conductivity of many

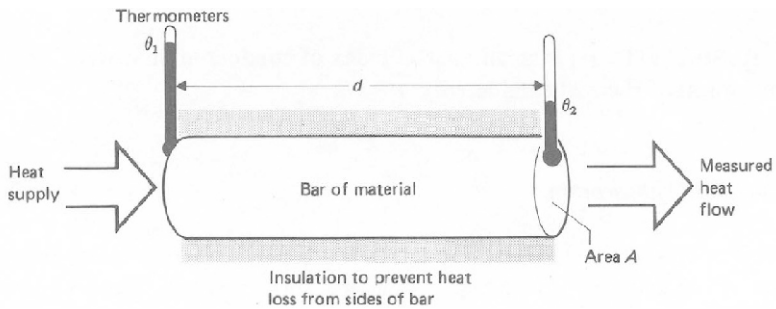


FIGURE 2.1 *Measurement of thermal conductivity*

TABLE 2.1 *Thermal conductivity of materials*

Material	k-value* (W/m °C)
Aluminium alloy, typical	160
Asbestos-cement sheet	0.40
Asphalt roofing, dry, typical	0.80
Brickwork, exposed (1700 kg/m^3)	0.84
Concrete, normal (2400 kg/m^3)	1.83
Concrete, lightweight (600 kg/m^3)	0.19
Copper, commercial	160
Corkboard	0.042
Fibre insulating board	0.050
Glass	1.022
Glass wool, mat or fibre	0.04
Hardboard, standard	0.13
Mineral wool	0.039
Plaster, gypsum	0.46
Plasterboard, gypsum	0.16
Polystyrene, expanded	0.033
Polystyrene, solid	0.17
Polyurethane, foam	0.026
PVC flooring	0.040
Steel, carbon	50
Stone, sandstone	1.3
Timber, softwood	0.13
Timber, hardwood	0.15
Woodwool slab	0.085

* Values adapted from the *CIBS Guide*.

building materials varies with moisture content. In the case of brickwork, concrete and stone the density also needs to be specified and more comprehensive tables of thermal conductivities should be used to obtain specific values.

RESISTIVITY (r) is an alternative index of conduction in materials and is the reciprocal of thermal conductivity: $r = 1/k$.

Emissivity and absorption

The ability of a material to absorb or give off radiant heat is a property of the surface of the material. Rough black surfaces absorb most heat and emit most heat. Conversely, shiny silvered surfaces absorb least heat and emit least heat.

To specify these properties of a surface coefficients of emission and absorption are used. They compare the behaviour of a particular surface to a theoretically perfect absorber and emitter called a 'black body', whose coefficient is given a value at one.

EMISSIVITY is the fraction of energy radiated by a body compared to that radiated by a black body at the same temperature.

Similarly, the *absorptivity*, or absorption factor, is the fraction of radiant energy absorbed by a body compared to that absorbed by a black body.

Values of emissivity and absorptivity depend upon the wavelength of the radiation and this is determined by the temperature of the source of the radiation. The Sun is a high temperature source of radiation and building materials are low temperature sources, so different sets of values may be quoted for the same surface. Table 2.2 gives typical values for common building surfaces.

TABLE 2.2 *Surface coefficients for building materials*

Surface	Emissivity (low temperature radiation)	Absorptivity (solar radiation)
Aluminium	0.05	0.2
Asphalt	0.95	0.9
Brick (dark)	0.9	0.6
Paint – white	0.9	0.3
Paint – black	0.9	0.9
Slate	0.9	0.9

In general, the colour of most building materials has little effect on the heat emitted from the building but has an important effect on the heat absorbed by the building from the Sun.

At night time a building emits radiant heat to its surroundings and the rate of this heat loss from the building will be increased if the night sky is clear and cloudless. This occurs because a clear sky is closer in form to a black body than a cloudy sky and so acts as a better absorber of radiant heat. As a result of 'clear sky radiation' from a building the temperature of a roof, for example, can fall below the temperature of the outside air.

U-VALUES

Heat is transferred through an element of a building, such as a wall, by a number of mechanisms. Layers of different materials conduct heat at different rates. In any cavity there is heat transfer by conduction and convection in the air and by radiation effects. At the inside and outside boundaries of the wall radiation and convection at the surface affect the rate of heat transfer.

It is convenient to combine all these factors into a single measurement describing the behaviour of the complete structural element. This measurement is called the overall thermal *transmittance coefficient*, or *U*-value.

> **A *U*-VALUE is a measure of the overall rate at which heat is transmitted through a particular thickness of wall, roof, or floor.**
>
> UNIT: $W/m^2\ °C$.

The coefficient, or *U*-value, is measured as the rate of heat flow in watts through 1 m^2 of a structure when there is a temperature difference across the structure of 1 °C.

The lower the *U*-value then the better the insulation. For example, a wall with a *U*-value of 0.5 $W/m^2\ °C$ loses heat at half the rate of a wall with a *U*-value of 1.0 $W/m^2\ °C$. So the cost of replacing heat lost through the first wall will be half that of the second wall.

Standard U-values

Standard *U*-values are calculated by making certain assumptions about moisture contents of materials and about rates of heat transfer at surfaces and in cavities. Although the standard assumptions represent practical conditions as far as possible, they will not always agree exactly with *U*-values measured on site.

However, the standard *U*-values are needed as a common basis for comparing the thermal insulation of different types of structure and for predicting the heat losses from buildings. Standard *U*-values are also used to specify the amount of thermal insulation required by clients or by regulations.

Typical *U*-values of some common types of construction are given in table 2.3.

TABLE 2.3 *Typical U-values of some constructions*

Element	Composition	*U*-value ($W/m^2\ °C$)
Solid wall	brickwork, 215 mm plaster, 15 mm	2.3
Cavity wall	brickwork, 102.5 mm unventilated cavity, 50 mm brickwork, 102.5 mm	1.6
Cavity wall	brickwork, 102.5 mm unventilated cavity, 50 mm aerated concrete block, 100 mm lightweight plaster, 13 mm	0.96

TABLE 2.3 continued

Element	Composition	U-value (W/m^2 °C)
Cavity wall	brickwork, 102.5 mm unventilated cavity, 25 mm polystyrene board, 25 mm aerated concrete block, 100 mm lightweight plaster, 13 mm	0.58
Cavity wall	brickwork, 102.5 mm glass fibre batts, 50 mm lightweight concrete block, 100 mm lightweight plaster, 13 mm	0.49
Cavity wall Timber Frame	brickwork, 102.5 mm unventilated cavity, 50 mm fibreboard, 13 mm mineral wool, 50 mm (inside timber frame, 100 mm) plasterboard, 13 mm	0.46
Window	single glazing metal frame	5.7
Window	double glazing airspace, 20 mm metal frame	2.8
Pitched roof	tiles on battens and felt ventilated airspace mineral fibre, 100 mm plasterboard, 9.5 mm	0.33
Flat roof	bitumen felt, 10 mm glass fibre roof board, 50 mm vapour barrier dense concrete slab, 150 mm lightweight plaster, 15 nm	0.51
Ground floor	plastics floor finish screed, 65 mm mineral fibre, 25 mm dense concrete base, 100 mm	0.6 (3 m square)
Ground floor	softwood floor boards, 25 mm airspace mineral fibre, 75 mm ventilated airspace	0.33 (3 m square)

Calculation of *U*-values is treated later in the chapter. Note that the *U*-values of floors are affected by the length of perimeter exposed to the outside.

Thermal regulations

Legislation for the thermal performance of buildings is a relatively recent concern. One method of conserving the heat energy used in buildings is to enforce minimum standards of thermal insulation. The control of other factors should also be considered, in particular ventilation rates, internal air temperatures, efficiency of plant and utilisation of buildings.

The intention of the 1965 United Kingdom Building Regulations concerning thermal insulation was to ensure minimum standards of health and comfort and to reduce the risk of condensation. The 1976 Building Regulations and amendments specifically mention the conservation of fuel and include non-residential buildings.

Figure 2.2 and table 2.4 give an outline of some important standards specified by the Building Regulations. The standards are expressed in terms of maximum *U*-values and maximum percentages of glazing. In some cases, increased areas of glazing are permitted provided that the overall rate of heat loss, in W/m^2 °C, remains the same. The regulations apply only to new buildings so the legislation

TABLE 2.4 *Thermal regulations for buildings*

Purpose of building	Structural element	Maximum *U*-value	Maximum glazing, %
Dwelling	External wall	0.6	12
	Roof	0.35	
Institutional, residential	Walls	0.6	20
	Roofs	0.6	25
	Exposed floors	0.6	
Office, shop, place of assembly, general	Walls	0.6	20
	Roofs	0.6	35
	Exposed floors	0.6	
Factory, storage	Walls	0.7	20
	Roofs	0.7	15
	Exposed floors	0.7	

Note: The values are summarised from the Building Regulations for England and Wales Part F 1976 and Amendments 1981; Part FF 1978.

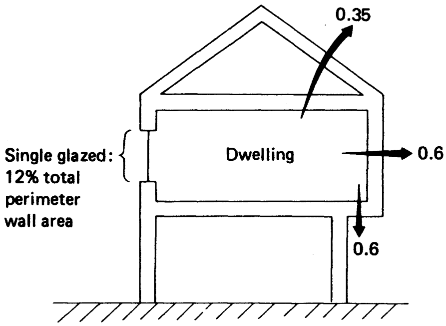


FIGURE 2.2 *Some maximum U-values for dwellings*

produces a long-term effect on national energy consumption, but gives immediate benefits to individual buildings.

Thermal resistance

U-values are calculated from the thermal resistances of the parts making up a particular part of a structure. The different layers and surfaces of a building element, such as a wall, transmit heat at different rates. These differences are described by thermal resistances, or '*R*-values'.

THERMAL RESISTANCE (*R*) is a measure of the opposition to heat flow given by a particular component in a building element

UNIT: m^2 °C/W.

The idea of thermal resistance is comparable to electrical resistance and a high thermal resistance reduces heat flow. So, for good thermal insulation high values of thermal resistance are required.

CONDUCTANCE (*C*) is sometimes used to express the reciprocal of thermal resistance: $C = 1/R$.

The following types of thermal resistance need to be determined.

(1) *Material Resistances* The thermal resistance of each layer of material in a structure depends on the rate at which the material conducts heat and the thickness of the material.

Assuming that a material is homogeneous the general formula is

$$\boxed{R = \frac{L}{k}}$$

where

R = thermal resistance of that component (m^2 °C/W)

L = thickness of the material (m)

k = thermal conductivity of the material (W/m °C)

Alternatively

$$R = rL$$

where

$$r = \frac{1}{k} = \textit{resistivity} \text{ of that material (m °C/W)}$$

(2) *Surface Resistances* The thermal resistance of an open surface depends upon the conduction, convection and radiation at that surface. The air in contact with a surface forms a stationary layer which opposes the flow of heat.

Factors which affect surface resistances are:

(a) whether the heat flow is upward or downward;
(b) whether the surfaces are sheltered or exposed;
(c) whether the surfaces are of normal building materials with high emissivity or polished metal with low emissivity.

Some standard surface resistances are given in table 2.5.

(3) *Airspace Resistances* The thermal resistance of an airspace depends on the nature of any conduction, convection and radiation within the cavity. Factors which affect this resistance are:

(a) the thickness of the airspace;
(b) whether the airspace is ventilated or unventilated;
(c) whether the airspace is lined with normal surfaces or reflective surfaces of low emissivity.

Some standard airspace resistances are given in table 2.5.

Total thermal resistance

The thermal resistances of the consecutive layers in a structural element, such as a wall or roof, can be likened to electrical resistances connected in series. Thus the total thermal resistance is the sum of the thermal resistances of *all* the components in a structural element. (N.B. Every type of structural element has *two* surface resistances – even single-glazed windows, for example.)

U-value

The thermal transmittance, or U-value, is calculated as the reciprocal of the total thermal resistance.

$$U = \frac{1}{R_{si} + R_1 + R_2 + \ldots R_a + R_{so}}$$

or

$$\boxed{U = \frac{1}{R_T}}$$

UNIT: W/m^2 °C. (*text cont. next page*)

TABLE 2.5 *Standard thermal resistances*

Type of resistance	Construction element	Heat flow	Surface emissivity*†	Standard resistances‡ (m^2 °C/W)
Inside surfaces	Walls	Horizontal	High Low	0.123 0.304
	Roofs – pitched or flat Ceilings Floors	Upward	High Low	0.106 0.218
	Ceilings Floors	Downward	High Low	0.150 0.562
Outside surfaces (normal exposure)‡	Walls	Horizontal	High Low	0.055 0.067
	Roofs	Upward	High Low	0.045 0.053
Airspaces (including boundary surfaces)	Unventilated, 5 mm	Horizontal or Upward	High Low	0.11 0.18
	Unventilated, 20 mm or greater	Horizontal or Upward	High Low	0.18 0.35
	Ventilated loft space with flat ceiling, unsealed tiled pitched roof			0.11

* High emissivity is for all normal building materials, including glass.
† Low emissivity is for untreated metallic surfaces such as aluminium or galvanised steel.
‡ Normal exposure is for most suburban and country premises.
‡ Further standard resistances are quoted in the *CIBS Guide* or *BRE Digest 108*.

where

U = U-value

R_T = sum of all component thermal resistances

R_{si} = standard inside surface resistance

R_1, R_2 = resistance of that particular material

R_a = standard resistance of any airspace

R_{so} = standard outside surface resistance

* * * * *

Worked example 2.1

Calculate the U-value of a cavity wall with a 105 mm thick brick outerleaf, a 50 mm unventilated cavity, then a 100 mm aerated concrete block inner leaf with a 15 mm layer of lightweight plaster. Thermal conductivities in W/m °C are: brickwork 0.84, aerated concrete blocks 0.19, lightweight plaster 0.16. Standard thermal resistances in m² °C/W are: internal surface 0.123, external surface 0.055, cavity 0.18.

Step 1 Sketch a diagram indicating all parts of the construction and surface layers.

Step 2 Tabulate all information and, where necessary, calculate thermal resistance using $R = L/k$.

Layer	Thickness (m)	Conductivity (W/m °C)	Resistance (m² °C/W)	
Internal surface			Standard	= 0.123
Lightweight plaster	0.015	0.16	0.015/0.16	= 0.094
Aerated concrete	0.100	0.19	0.1/0.19	= 0.526
Cavity	0.050		Standard	= 0.18
Brickwork	0.105	0.84	0.105/0.84	= 0.125
External surface			Standard	= 0.055
			Total resistance	1.103

Step 3 Using $U = \dfrac{1}{R_T}$

$$U = \frac{1}{1.103} = 0.9066$$

U-value = **0.91 W/m² °C**

* * * * *

Adjustments to U-values

It is sometimes necessary to calculate the effect that additional insulating material has upon a U-value, or to calculate what thickness of material is required to produce a specified U-value.

U-values cannot be added together or subtracted from one another. Thermal resistances however can be added and subtracted and the resistances making up a particular U-value are adjusted to produce the new U-value. Worked example 2 illustrates the technique.

* * * * *

Worked example 2.2

A plain cavity wall, such as in worked example 2.1, would have a U-value of 0.91 W/m² °C. If expanded polystyrene board is included in the construction what minimum thickness of this material is required to reduce the U-value to 0.6 W/m² °C? Given that the thermal conductivity of the expanded polystyrene board = 0.033 W/m °C.

New U-value	$U_2 = 0.6$
New total resistance $(1/U)$	$R_2 = 1.667$
Existing U-value	$U_1 = 0.91$
Existing total resistance $(1/U)$	$R_1 = 1.099$
Extra resistance required	$R_2 - R_1 = 0.568$
k-value of insulating material	$k = 0.033$
Thickness of material	$L = R \times k = 0.0187$ m

So minimum thickness of insulating board needed = **19 mm**

* * * * *

Average U-values

If a wall, or other element, is composed of different constructions with different U-values then the overall insulation of the wall depends upon the relative areas of the different constructions. For example, if a wall contains two-thirds brickwork and one-third windows then the U-values of the brickwork and windows must be combined in the proportions of $\frac{2}{3}$ and $\frac{1}{3}$ to give the average U-value for the wall.

The general formula is as follows

$$U\,(\text{average}) = \frac{A_1U_1 + A_2U_2 + \ldots}{A_1 + A_2 + \ldots}$$

where

$A_1, A_2, \ldots$ are the areas with the U-values U_1, $U_2, \ldots$ etc.

* * * * *

Worked example 2.3

A brick wall has a total area of 8 m^2 of which 2 m^2 are windows. The U-values are 0.95 W/m^2 °C for the brickwork and 2.8 W/m^2 °C for the windows. Calculate the average U-value for the wall.

$U_1 = 0.95$; $A_1 = 8 - 2 = 6$; $U_2 = 2.8$; $A_2 = 2$;

U (average) = ?

Using $$U = \frac{A_1U_1 + A_2U_2}{A_1 + A_2}$$

$$U = \frac{(6 \times 0.95) + (2 \times 2.8)}{6 + 2} = \frac{5.7 + 5.6}{8}$$

Average U-value = **1.41 W/m^2 °C**

* * * * *

Thermal bridges

When a material of high thermal conductivity passes completely through a wall, floor, or roof then that area is said to be 'bridged' and the effective U-value is lowered.

A THERMAL BRIDGE is a portion of a structure whose high thermal conductivity lowers the overall thermal insulation of the structure.

The heat flow in the area of this 'cold bridge' is increased and the surface temperatures are lowered, increasing the risk of condensation on these surfaces.

Thermal bridges can easily occur when the insulation of a wall is bridged at the junctions with the floor, the roof, or the windows. Some examples of thermal bridges are shown in figure 2.3. The remedy for thermal bridging is the correct design and installation of thermal insulation.

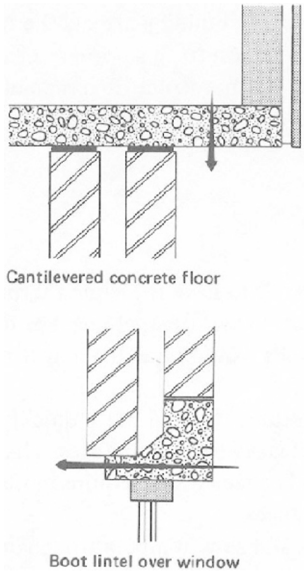


FIGURE 2.3 *Thermal bridges*

Pattern staining

Pattern staining on a ceiling is the formation of a pattern, in dirt or dust, which outlines the hidden structure of the ceiling. It is a particular result of thermal bridging and also depends upon the frequency of redecoration. The areas of lower insulation transmit heat at a higher rate than the surrounding areas – between the joists shown in figure 2.4, for example. The convection patterns

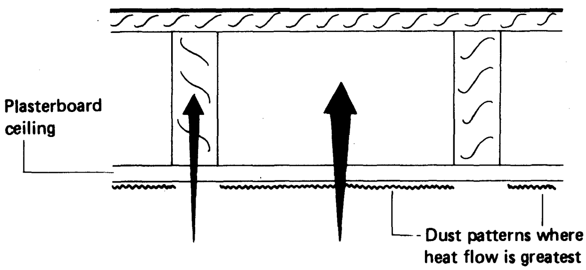


FIGURE 2.4 *Pattern staining*

which then occur cause a greater accumulation of airborne dirt on these areas.

There is a risk of pattern staining occurring if the difference between surface temperatures exceeds 1 °C, which is unlikely in a modern well-insulated roof.

STRUCTURAL TEMPERATURES

The thermal insulation installed in a building affects the rate at which the building loses heat energy. In addition to this primary effect the type of insulating material and its position in a structure has an effect upon the temperatures inside the building and the temperatures inside the structural elements.

Response times

It is possible for two types of wall to have the same thermal insulation, as measured by *U*-values, but to absorb or dissipate heat at different rates. As a result the rooms inside such walls would take different times to warm or to cool, as indicated in figure 2.5.

In general, lightweight structures respond more quickly to surrounding temperature changes than do heavyweight structures. This is because heavyweight materials have a higher thermal capacity and require more heat energy to produce given temperature changes.

The heat storage properties and slow temperature changes of heavyweight materials, such as concrete and brick, can be useful if thoughtfully designed. Where quick heating is often required, in bedrooms for example, a lightweight structure may be more useful. Or the heating-up time of heavyweight construction can be reduced by insulating the internal surfaces, by carpeting a concrete floor for example.

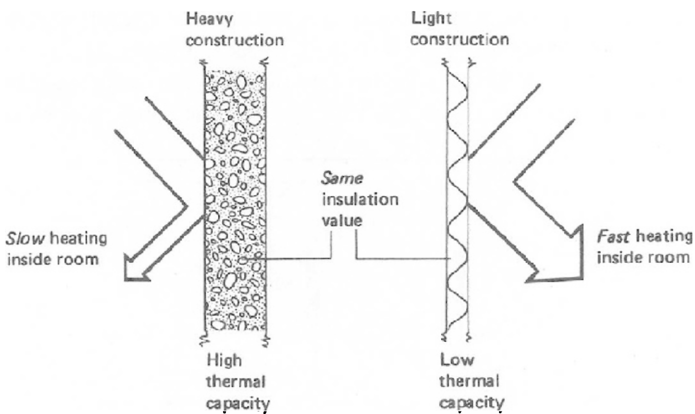


FIGURE 2.5 *Thermal response*

Temperature gradients

A temperature difference between the inside and outside of a wall or roof causes a progressive change in temperature from the warm side to the cold side. This *temperature gradient* changes uniformly through each component, provided that the material is homogeneous and that the temperatures remain constant.

A structure made up of different materials, such as the wall shown in figure 2.6, will have varying temperature gradients between the inside and outside. The layers with the highest thermal resistances will have the steepest gradients. This is because the best insulators must have the greatest temperature differences between their surfaces.

The *boundary temperatures* between layers in a structural element can be determined from the thermal resistances which make up the *U*-value of that element.

The ratio of the temperature changes inside a structure is proportional to the ratio of the thermal resistances.

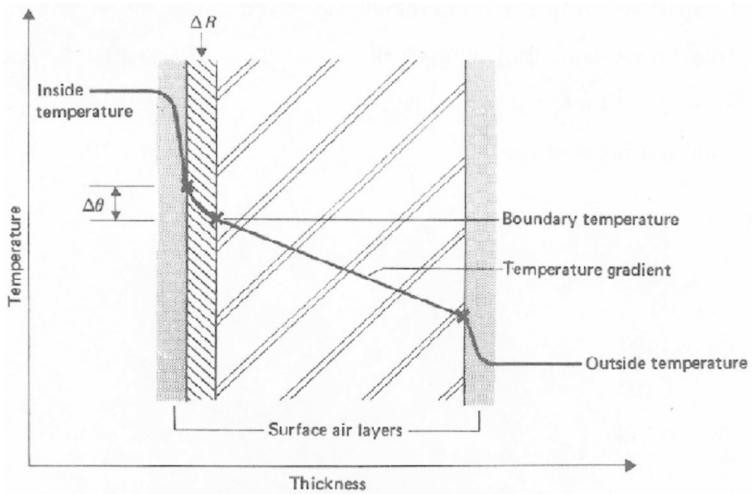


FIGURE 2.6 *Temperature gradients through a wall*

The most useful relationship is given by the formula

$$\frac{\Delta\theta}{\theta_T} = \frac{\Delta R}{R_T}$$

where

$\Delta\Theta$ = temperature difference across a particular layer

ΔR = resistance of that layer

θ_T = total temperature difference across the structure

R_T = total resistance of the structure

From this relationship the temperatures at boundaries in a structure can be predicted for specified conditions. A calculation of all the boundary temperatures allows temperature gradients to be drawn on a scaled diagram. These diagrams can be used to predict zones of possible condensation, as in chapter 4.

* * * * *

Worked example 2.4

The wall described in Worked Example 2.1 is an external wall of a room containing air at 20 °C when the outside temperature is 5 °C. Calculate the boundary temperature on the internal surface of the wall.

Temperature drop across internal surface layer	$\Delta\theta$ = ?
Total temperature drop across wall	$\theta_T = 20 - 5 = 15\,°$
Resistance of internal surface layer	$R_{si} = 0.123$
Total resistance of the wall	$R_T = 1.103$

Using

$$\frac{\Delta\theta}{\theta_T} = \frac{\Delta R}{R_T}$$

$$\frac{\Delta\theta}{15} = \frac{0.123}{1.103}$$

$$\Delta\theta = \frac{0.123}{1.103} \times 15 = 1.67$$

Temperature drop across internal surface layer = 1.67 °C

So temperature on the inside surface = 20 – 1.67 = **18.33 °C**

* * * * *

EXERCISES

1 Describe the physical properties of three different insulating materials used in modern buildings and explain how they are used in construction.

2 Explain the differences between the following terms:
(a) thermal conductivity;
(b) thermal resistance; and
(c) thermal bridging.

3 A cavity wall is constructed as follows: brickwork outer leaf 105 mm, air gap 25 mm, expanded polystyrene batt 25 mm, aerated concrete block inner leaf 100 mm, plasterboard 10 mm. The relevant values of thermal conductivity, in W/m °C, are: brickwork 0.84, polystyrene 0.035, concrete block 0.19, plasterboard 0.16. The standard thermal resistances, in m^2 °C/W are: outside surface 0.055, inside surface 0.123, air gap 0.18.
(a) Calculate the *U*-value of this wall.
(b) Calculate the *U* value of the same wall sited in a position of severe exposure for which the outside surface resistance is 0.03 m^2 °C/W.

4 The cavity wall of a house has outer and inner brickwork leaves each 105 mm with a 50 mm air gap between them and a 16 mm inside layer of plaster. The relevant values of thermal conductivity, in W/m °C, are: brickwork 0.73, plaster 0.46. The standard thermal resistances, in m^2 °C/W, are: outside surface 0.055, inside surface 0.123, air gap 0.18.
(a) Calculate the *U*-value of the existing wall.
(b) Calculate the *U*-value of the wall if the cavity is completely filled with foamed urea formaldehyde ($k = 0.026$ W/m °C).

5 Compare the *U*-values obtained in questions 3 and 4 with the *U*-values required in current Building Regulations. Comment on the suitability of the walls for different purposes.

6 Compare the *U*-values of a single-glazed window made up of one sheet of 4 mm glass with a double glazed window made up of two sheets of 4 mm glass which have a 5 mm airspace between them. The thermal conductivity of the glass is 1.022 W/m °C. The standard thermal resistances, in m^2 °C/W, are: outside surface 0.055, inside surface 0.123, airspace 0.11. Comment on the significance of the thermal resistance provided by the glass layers. Comment on the effect of the window frames.

7 A brickwork wall measures 5 m x 2.8 m in overall length and height. The wall contains one window 1400 mm by 800 mm and one door 1900 mm by 750 mm. The *U*-values, in W/m^2 °C, are: brickwork 0.95, window 5.6, door 3.4. Calculate the average *U*-value of this wall.

8 A pre-cast wall panel is to have the following cross section: 75 mm of dense concrete, a layer of expanded polystyrene, and 150 mm of lightweight concrete. The values of thermal conductivity, in W/m °C are: dense concrete 1.45, expanded polystyrene 0.034, lightweight concrete 0.23. The standard thermal resistances, in m^2 °C/W, are: outside surface 0.055, inside surface 0.123. Calculate the minimum thickness of polystyrene required to give the wall panel a *U*-value of 0.6 W/m^2 °C.

9 A domestic pitched roof of tiles on felt sacking, with a plasterboard ceiling, has a *U*-value of 1.9 W/m^2 °C. Calculate the minumum thickness

of fibreglass insulation in the roof space required to give the roof a new *U*-value of 0.6 W/m^2 °C. The thermal conductivity of the fibreglass quilting used is 0.04 W/m °C.

10 A wall has a *U*-value of 2.5 W/m^2 °C. The thermal resistance of the inside surface layer is 0.123 m^2 °C/W. The inside air temperature is 18 °C and the outside air temperature is 0 °C. Calculate the temperature on the inside surface of the wall.

ANSWERS

3 0.56 W/m^2 °C; 0.57 W/m^2 °C
4 1.47 W/m^2 °C; 0.41 W/m^2 °C
6 5.49 W/m^2 °C; 3.38 W/m^2 °C
7 1.57 W/m^2 °C
8 27 mm
9 46 mm
10 12.5 °C

3 Thermal Environment

A satisfactory thermal environment is an important aim of good building design. To achieve this aim the requirements of the people or the articles in the building need to be known. The mechanisms causing heat to be lost from the building can be identified and the heat losses calculated.

Heat gains, such as those from the Sun or from electrical appliances, also need to be taken into account. From such considerations it is possible to design the correct type of heating and cooling plant, to predict the energy consumption and the running costs.

THERMAL COMFORT

The thermal comfort of human beings is governed by many physiological mechanisms of the body and these vary from person to person. In any particular thermal environment it is difficult to get more than 50 per cent of the people affected to agree that the conditions are comfortable!

The body constantly produces heat energy from the food energy it consumes. This heat needs to be dissipated at an appropriate rate to keep the body at constant temperature. The transfer of the heat from the body is mainly by the processes of convection, radiation and evaporation. Evaporation transfers the latent heat we give to the water vapour which is given out on the skin (perspiration) and in the breath (respiration).

The total quantity of heat produced by a person depends upon the size, the age, the sex, the activity and the clothing of the person. A further complication is the ability of the body to become accustomed to the surrounding conditions and to adapt to them. For example, everyone can tolerate slightly lower temperatures during winter. This adaption can be influenced by the type of climate and the social habits of a country.

Factors affecting thermal comfort

The principal factors affecting thermal comfort can be conveniently considered under the following headings and are discussed further in the sections below.

Personal variables

1. Activity.
2. Clothing.
3. Age.
4. Sex.

Physical variables

1. Air temperature.
2. Surface temperatures.
3. Air movement.
4. Humidity.

Activity

The greater the activity of the body the more heat it gives off. The rate of heat emission depends upon the individual metabolic rate of a person and upon their surface area. People who seem similar in all other respects can vary by 10 to 20 per cent in their heat output.

The average rate of heat emission decreases with age. Table 3.1 lists typical heat outputs from an adult male for a number of different activities. The output from adult females is about 85 per cent that of males.

TABLE 3.1 *Heat output of human body*

Activity	Example	Typical heat emission of adult male
Immobile	Sleeping	70 W
Sitting	Watching television	115 W
Light work	Office	140 W
Medium work	Factory, dancing	265 W
Heavy work	Lifting	440 W

Clothing

Clothes act as a thermal insulator for the body and help to maintain the skin at a comfortable temperature. Variations in clothing have a significant effect on the surrounding temperatures that are required for comfort.

To enable heating needs to be predicted a scale of clothing has been developed – the clo-value. 1 clo represents 0.155 m^2 °C/W of insulation and values range from 0 clo to 4 clo. Table 3.2 shows the value of different types of clothing and

TABLE 3.2 *Clothing values*

clo value	Clothing example*	Typical comfort temperature when sitting (°C)
0 clo	Naked; swimwear	29
0.5 clo	Light trousers, shirt; light dress, blouse	25
1.0 clo	Business suit; dress, jumper	22
2.0 clo	Heavy suit, overcoat, gloves, hat	14

* Appropriate underclothing is assumed in each case.

indicates how the room temperature required for comfort varies with clothing. On average, women prefer slightly higher temperatures.

Room temperatures

The temperature of the surrounding surfaces can affect the thermal comfort of people as much as the temperature of the surrounding air. This is because the rate at which heat is radiated from a person is affected by the radiant properties of the surroundings. For example, when sitting near the cold surface of a window the heat radiated from the body increases and can cause discomfort.

A satisfactory design temperature for achieving thermal comfort needs to take account of both air temperatures and surface temperatures. The different types of temperatures are specified below.

Internal Air Temperature, t_{ai} (°C) This is the ordinary dry bulb temperature of the air (°C).

Mean Radiant Temperature, t_r (°C) This is the average effect of radiation from surrounding surfaces. This temperature can usually be taken as being equal to the mean surface temperature as calculated by

$$t_r = \frac{A_1 t_1 + A_2 t_2 + \ldots}{A_1 + A_2}$$

where $t_1, t_2 \ldots$ are the surface temperatures of the areas $A_1, A_2, \ldots$, etc.

Environmental Temperature, t_{ei} (°C) This is a combination of air temperature and radiant temperature derived from the formula

$$\boxed{t_{ei} = \tfrac{2}{3} t_r + \tfrac{1}{3} t_{ai}}$$

Dry Resultant Temperature, t_{res} (°C) This is a combination of air temperature, radiant temperature and air movement. When the air movement is low it can be derived from the formula

$$t_{res} = \tfrac{1}{2}t_r + \tfrac{1}{2}t_{ai}$$

Comfort Temperature, t_c (°C) This is a temperature giving close agreement with the comfort state. Both environmental temperature (t_{ei}) and dry resultant temperature (t_{res}) have been used for design purposes. Table 3.3 gives a list of typical comfort temperatures.

The *globe thermometer* is a regular thermometer fixed inside a blackened globe of specified diameter (150 mm is one standard). This globe temperature can be used to calculate other temperatures and when air movement is small it approximates to the comfort temperature.

The mean radiant temperature should be kept near the air temperature but not more than about 3 °C below it, otherwise conditions are sensed as stuffy.

TABLE 3.3 *Some design temperatures and infiltration rates*

Type of building	Design temperature t_{ei} (°C)	Infiltration, air changes per hour*
Domestic		
living rooms	21	1
bedrooms	18	½
bathrooms	22	½
Offices, general	20	1
Classrooms, school	18	2
Shops, large	18	½
Restaurants; bars	18	1
Hotel bedrooms	22	1
Factories, light work	16	

* Conversion from air changes per hour to ventilation heat loss is: 1 air change per hour = 0.34 W/m^2 °C.

Air movement

The movement of air in a room helps to increase heat lost from the body by convection and can cause the sensation of draughts. The back of the neck, the forehead and the ankles are the most sensitive areas for chilling. As the speed of air movement in a room increases above 0.1 m/s then higher air temperatures are required to give the same degree of comfort. For example, if air at 18 °C increases in movement from 0.1 m/s to 0.2 m/s then the temperature of the air needs to rise to 21 °C to avoid discomfort.

The air movement rate is *not* the same thing as the air change rate and is not always caused by ventilation. Uncomfortable air movement may be due to natural convection currents, especially near windows or in rooms with high ceilings.

A *hot-wire anemometer* or a *Kata thermometer* may be used to measure air movement. Both devices make use of the cooling effect of moving air upon a thermometer.

Humidity

Humidity is caused by moisture in the air and will be treated more fully in chapter 4. For comfortable conditions the relative humidity should be kept within the range 40 to 70 per cent.

High humidities and high temperatures feel oppressive and natural cooling by perspiration is decreased. High humidity and low temperatures cause the air to feel chilly.

Low humidities can cause dryness of throats and skin. Static electricity can accumulate with low humidity, especially in modern offices with synthetic carpet, and cause mild but uncomfortable electric shocks.

Ventilation

In any occupied space ventilation is necessary to provide oxygen and to remove contaminated air. Fresh air contains about 21 per cent oxygen and 0.04 per cent carbon dioxide while expired air contains about 16 per cent oxygen and 4 per cent carbon dioxide. The body requires a constant supply of oxygen but the air would be unacceptable well before there was a danger to life. As well as being a comfort consideration the rate of ventilation has a great effect on the heat loss from buildings and on condensation in buildings.

The normal process of breathing gives significant quantities of latent heat and water vapour to the air. Household air is also contaminated by body odours, bacteria, and the products of smoking, cooking and washing. In places of work, contamination may be increased by a variety of gases and dusts.

A number of statutory regulations specify minimum rates of air-supply in occupied spaces. Recommended rates of ventilation depend upon the volume of a room, the number of occupants, the type of activity and whether smoking is expected. It is difficult therefore to summarise figures for air-supply but table 3.4 quotes some typical values.

TABLE 3.4 *Typical fresh air-supply rates*

Type of space	Recommended air-supply
Residences; offices; shops	8 litres/s per person
Restaurants; bars	18 litres/s per person
Kitchens; domestic toilets	10 litres/s per m^2 floor

HEAT LOSSES

Factors affecting heat loss

Heat loss from a building occurs by a number of mechanisms, as illustrated in figure 3.1. Some important factors which affect the rate at which this heat is lost are summarised below.

(1) *Insulation of the Shell* The external parts of the structure surrounding occupied areas need most consideration but all buildings which are heated, for whatever purpose, should be well insulated in order to save energy. The overall

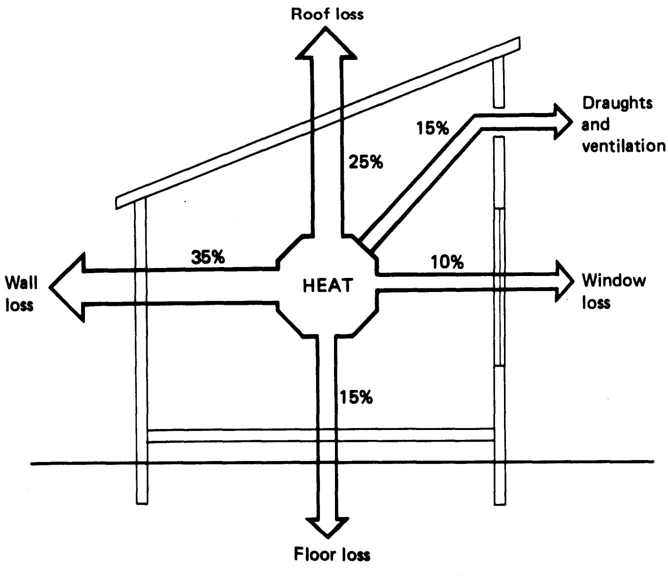


FIGURE 3.1 *Heat losses in a building*

thermal transmittance coefficient – the *U*-value – of a construction is a commonly used index of insulation.

(2) *Area of the Shell* The greater the area of external surfaces the greater is the rate of heat loss from the building. A terraced house, for example, loses less heat than a detached house of similar size. Table 3.5 compares exposed perimeter areas for different shapes of dwelling.

The basic plan shape of a building is one of the first design decisions to be made, although choices may be restricted by the nature of the site and by local regulations.

TABLE 3.5 *Exposed areas of dwellings*

Type of dwelling (each of same floor area)	Exposed perimeter area, %
Detached house	100
Semi detached house	81
Terraced house	63
Flat on middle storey (2 external walls)	32

(3) *Difference in Temperature* A large difference between the temperatures inside and outside the building increases the rate of heat lost by conduction and ventilation. This loss is affected by the design temperature of the internal air, which depends upon the purpose of the building. Recommended comfort temperatures for different types of buildings are given in table 3.3.

(4) *Air Change Rate* Warm air leaving a building carries heat and is replaced by colder air. The air flow occurs through windows, doors, gaps in construction, ventilators and flues. This air change may be controlled ventilation or it may be accidental infiltration.

The rate of air change is also affected by effects of wind upon the building. Table 3.3 gives typical rates of air infiltration which are found to exist in buildings on sites of normal exposure during winter heating conditions.

(5) *Exposure and Orientation* When a wind blows across a wall or roof surface the rate of heat transfer through that element increases. This effect is included in the standard value of external surface resistance used in calculating a *U*-value. Standard surface resistances are available for three types of exposure:

(a) *Sheltered*: Building up to 30 storeys in city centres.
(b) *Normal*: Most suburban and country buildings.

(c) *Severe*: Buildings on exposed hills or coastal sites. Floors above the fifth in suburban or country sites. Floors above the ninth in city centres.

(6) *Design of Services* There is usually some wastage of heat energy used for water heating and space heating and the design of the services can often minimise or use this waste heat. For example, some of the heat from the hot gases passing up a flue can help heat the building if the flue is positioned internally rather than on an external wall.

The heat given off by hot water storage cylinders and distribution pipes, even well-insulated ones, should be used inside the building if possible rather than wasted outside. Even the draining away of hot washing water, dirty but full of heat energy, is a heat loss from the building; and a heat gain to the sewerage system!

Calculation of heat loss

Several methods are available for calculating the amounts of heat lost from buildings. Variations in outside temperatures, in solar radiation and in the heat stored in building materials make a full calculation difficult.

However, certain simplified calculations can be used for predicting heating requirements and the amount of fuel required. The results obtained by these calculations are found to give adequate agreement with the conditions that actually exist.

With *steady state conditions* the temperatures inside and outside the building do not change with time and the various flows of heat from the building occur at constant rates. Assuming steady state conditions the heat losses from a building can be classed as either a fabric loss or a ventilation loss and then calculated by the methods described below.

Fabric Loss Fabric heat loss from a building is caused by the transmission of heat through the materials of walls, roofs and floors. Assuming steady state conditions the loss for each element can be calculated by the following formula:

$$\boxed{P_f = UA\theta}$$

where

P_f = rate of fabric heat loss = $\frac{Q}{t}$ (W)

U = U-value of the element considered (W/m^2 °C)

A = area of that element (m^2)

θ = difference between the design temperatures assumed for the internal and external environments (°C)

The inside design temperature would be the appropriate environmental or comfort temperature, as quoted in table 3.3. The outside air temperature is commonly used as the external design temperature for winter conditions.

Conditions not suited to the steady state assumption occur when there is intermittent heating, such as that given by electric storage heaters or by solar radiation. The thermal capacity of the structure is then significant and needs to be considered in the calculation.

The *admittance* value expresses the ability of a building surface to smooth out temperature variations over a period of time. Heavyweight structures have different admittance values to lightweight ones. Methods of calculation using admittance values are available.

Ventilation Loss Ventilation heat loss from a building is caused by the loss of warm air and its replacement by air that is colder and has to be heated. The rate of heat loss by such ventilation or infiltration is given by the following formula

$$\boxed{P_v = \frac{c_v N V \theta}{3600}}$$

where

P_v = rate of ventilation heat loss = $\frac{Q}{t}$ (W)

c_v = volumetric specific heat capacity of air

= specific heat capacity x density (J/m^3 °C)

N = air infiltration rate for the room (the number of complete air changes per hour)

V = volume of the room (m^3)

θ = difference between the temperatures of the internal and external air (°C)

The values for the specific heat capacity and seconds in an hour are sometimes combined into a factor of 0.33 to give the formula

$$\boxed{P_v = 0.33 N V \theta}$$

* * * * *

Worked example 3.1

A window measuring 2 m by 1.25 m has an average *U*-value, including the frame, of 6.2 W/m^2 °C. Calculate the rate of fabric heat loss through this window when the inside comfort temperature is 20 °C and the outside air temperature is 4 °C.

$$U = 6.2 \text{ W/m}^2\ °\text{C}, A = 2 \times 1.25 = 2.5 \text{ m}^2, \theta = 20 - 14 = 16\ °\text{C}.$$

Using

$$P_f = UA\theta$$

$$= 6.2 \times 2.5 \times 16 = 248$$

fabric loss = **248 W**

Worked example 3.2

A simple building is 4 m long by 3 m wide by 2.5 m high. In the walls there are two windows each 1 m by 0.6 m and there is one door 1.75 m by 0.8 m. The construction has the following *U*-values in W/m^2 °C: windows 5.6, door 2.0, walls 2.5, roof 3.0, floor 1.5. The inside environmental or comfort temperature is maintained at 18 °C while the outside air temperature is 5 °C. The volumetric specific heat capacity of the air is taken to be 1300 J/m^3 °C. There are 1.5 air changes per hour. Calculate the total rate of heat loss for the building under the above conditions.

Step 1 Sketch the building with its dimensions as in figure 3.2. Calculate the areas and temperature differences.
Step 2 Tabulate the information and calculate fabric heat losses using $P_f = UA\theta$.

Element	*U*-value (W/m^2 °C)	Area (m^2)	Temperature difference (°C)	Rate of heat loss (W)
Window	5.6	1.2	12	80.64
Door	2.0	1.4	12	33.6
Walls	2.5	35–2.6	12	972
Roof	3.0	12	12	432
Floor	1.5	12	12	216
		Total fabric heat loss =		1734.24 W

Step 3 Calculate the ventilation heat loss.

$$c_v = 1300 \text{ J/m}^3\ °\text{C}, \quad N = 1.5 \text{ h}^{-1}$$

$$V = 4 \times 3 \times 2.5 = 30 \text{ m}^3, \quad \theta = 18 - 6 = 12\ °\text{C}$$

Using

$$P_v = \frac{c_v N V \theta}{3600}$$

$$= \frac{1300 \times 1.5 \times 30 \times 12}{3600} = 195$$

Ventilation heat loss = 195 W

Step 4

Total rate of heat loss = fabric heat loss + ventilation heat loss

= 1734.24 + 195

= **1929.24 W**

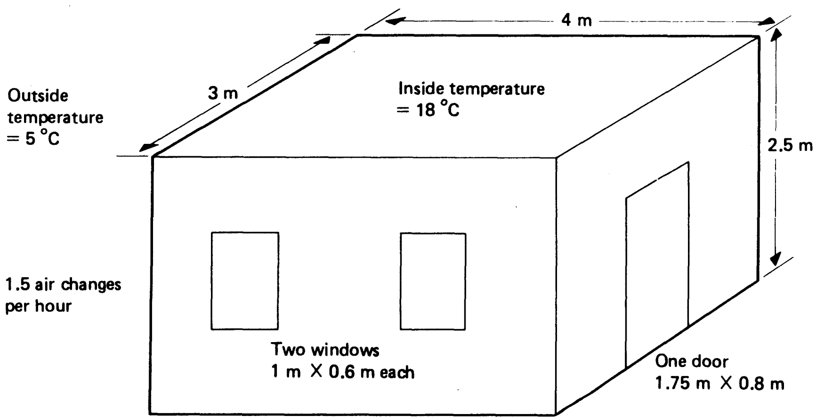


FIGURE 3.2 *Worked example 3.2*

* * * * *

HEAT GAINS

A building gains heat energy as well as losing it, and usually both processes occur at the same time. In a country with a temperate climate, such as the United Kingdom, the overall gains are less than the losses but the gains may still give useful energy savings. The factors affecting heat gains are indicated in figure 3.3 and discussed in the following sections.

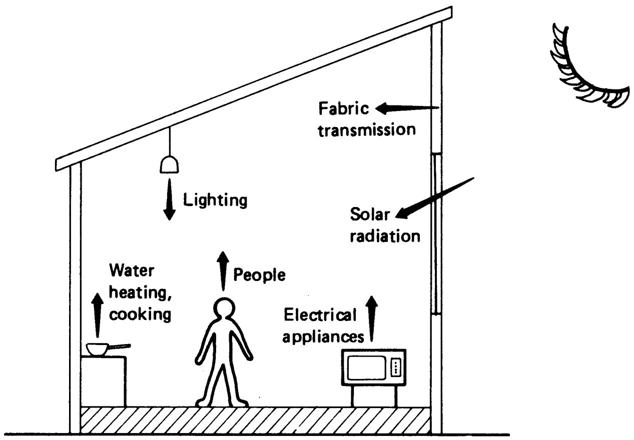


FIGURE 3.3 *Heat gains in a building*

Solar heat gain

The heat gained in a building by heat radiation from the sun depends upon the following factors:

1. the latitude of the site;
2. the orientation of the building on the site;
3. the season of the year;
4. the local weather;
5. the angles between the rays of the Sun and the building surfaces;
6. the type of windows;
7. the type of roof and walls.

The rate at which heat from the Sun falls on a surface varies throughout the day and the year. Figure 3.4 gives an indication of the intensity of solar radiation on a vertical and horizontal surface at different times. The figures are for London (latitude 51.7 °N) and assume cloudless days. The heat gains for other surfaces and locations can be calculated from appropriate tables and charts. The nature of Sun movements is described in the section on direct sunlight in chapter 7.

Most solar heat gain in UK buildings is by direct radiation through windows. The maximum gains through south-facing windows tend to occur in spring and autumn when the lower angle of the Sun causes radiation to fall more directly onto vertical surfaces. This type of heat gain, if used correctly, can be useful for winter heating. The fabric solar heat gains through walls and roofs are considered negligible for most United Kingdom buildings during the winter. This is because the high thermal capacity of heavyweight construction tends to delay transmission of the solar heat until its direction of flow is reversed with the arrival of evening.

The solar heat gains for a particular building at a specific time are relatively

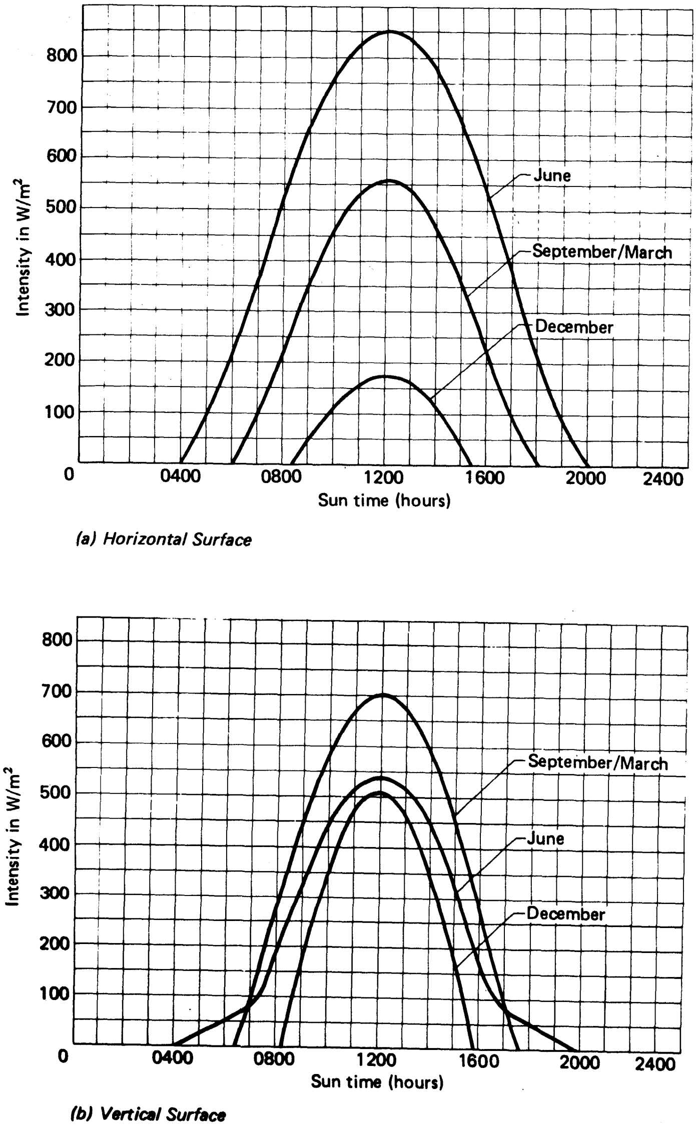


FIGURE 3.4 *Solar intensities, latitude 51.7 °N*

complicated to calculate, although it is important to do so when predicting summer heat gains. For winter calculations however, it is useful to consider the *total* solar gain over an average heating season.

The BRE have published figures for solar heat gain through the windows of typical buildings in Britain. These gains are the total for a standard heating season of 33 weeks and are shown in table 3.6.

TABLE 3.6 *Seasonal solar gain through windows*

Type of window (unobstructed)	Seasonal total heat gain
South-facing windows	680 MJ/m^2 glass
East and west windows	410 MJ/m^2 glass
North-facing windows	250 MJ/m^2 glass
Total for average semi-detached house	7500 MJ

Sun Controls Sun controls are parts of a building that help prevent excessive heat gain and glare caused by direct sunshine. The main types of device used are as follows:

1. *External controls* are the most effective form of Sun control. Examples include shutters, awnings, projecting eaves or floor slabs.
2. *Internal controls* give protection against glare and direct radiation but they can re-emit heat inside the room. Curtains and blinds, for example.
3. *Special glasses* are available which prevent the transmission of most heat radiation with only some loss of light transmission.

Sol-air temperature

In heating designs for buildings it is necessary to assume a temperature for the outside environment. For winter heating an overcast sky is assumed and the outside air temperature can be used for design purposes. For heat transfer calculations in summer it is necessary to take account of solar radiation as well as air temperature.

Sol-air Temperature (t_{eo}) This is an effective temperature for the outside air, which – in the absence of solar radiation – would give the same temperature distribution and rate of heat transfer as are given by the actual outdoor temperature and solar radiation.

Sol-air temperature varies with climate, time of day and incident radiation. Values can be calculated or found from tables of average values.

Casual heat gains

Casual heat gains take account of the heat given off by various activities and equipment in a building that are not primarily designed to give heat. The major sources of such heat are as follows:

1. heat from people;
2. heat from lighting;
3. heat from cooking and water heating;
4. heat from machinery, refrigerators, electrical appliances.

In commercial or public buildings this type of heat gain can be considerable and must be allowed for in the design of the heating/cooling system. Where possible this heat should be used rather than wasted. Table 3.7 gives the typical rate of heat output from various sources.

TABLE 3.7 *Heat emissions from casual sources*

Type of source	Typical heat emission
Human activity	
Seated at rest	115 W per person
Walking slowly	160 W per person
Dancing	265 W per person
Lighting	
Fluorescent system giving 400 lux (e.g. classroom)	20 W/m^2 floor area
Tungsten system giving 200 lux (e.g. domestic kitchen)	40 W/m^2 floor area
Equipment	
Computer printer unit	1100 W
Visual display unit (with fan)	800 W
Coffee urn, 14 litres	1200 W
Small Bunsen burner	600 W
Hair dryer	800 W
Gas gooker	3500 W per burner
Colour television, or hi-fi unit	100 W
Domestic fridge-freezer	150 W

In houses the casual heat gain is useful in winter and, as dwellings become better insulated, it forms a higher proportion of the total heat needed. The combined heat output of the various sources varies from hour to hour so it is again useful to consider the total heat gain over a standard heating system.

Table 3.8 quotes BRE estimates of the heat gains in a typical semi-detached house of 100 m^2 totalled over a heating season of 33 weeks.

ENERGY CONSUMPTION

Buildings in the British Isles, and in countries with a similar climate, suffer an

TABLE 3.8 *Domestic seasonal heat gains*

Source	Typical gain per heating season
Body heat (per person)	1000 MJ
Cooking (gas)	6500 MJ
Cooking (electric)	3500 MJ
Water heating	2000 MJ
Electricity (including lights)	3000 MJ

overall loss of heat during the year. The energy required to replace heat losses from buildings represents a major portion of the country's total energy consumption. Figure 3.5 gives an indication of energy use in the United Kingdom during the 1970s. Building services make up 40 to 50 per cent of the national consumption of primary energy and about half of this energy is used in domestic buildings.

Energy terms

PRIMARY ENERGY: The *gross* available energy contained in a raw fuel such as coal or oil.

DELIVERED ENERGY: The *net* energy content of a fuel measured as it is received by the consumer.

USEFUL ENERGY: The energy required to perform a given task.

EFFICIENCY: A measure of the effectiveness of any system which converts energy from one form to another.

$$\textbf{Efficiency} = \frac{\text{Output energy}}{\text{Input energy}} = \frac{\text{Useful energy}}{\text{Delivered energy}}$$

Calculation of Energy The quantity of delivered energy consumed over a given period depends upon both the power (rate of energy use) and upon the time involved.

Energy = Power x Time

$$\boxed{E = Pt}$$

UNIT: joule (J), where 1 joule = 1 watt x 1 second. Other units of energy include:

kilowatt hour (kWh), where 1 kWh = 3.6 MJ

British Thermal Unit (BTU), where 1 BTU = 1.055 kJ

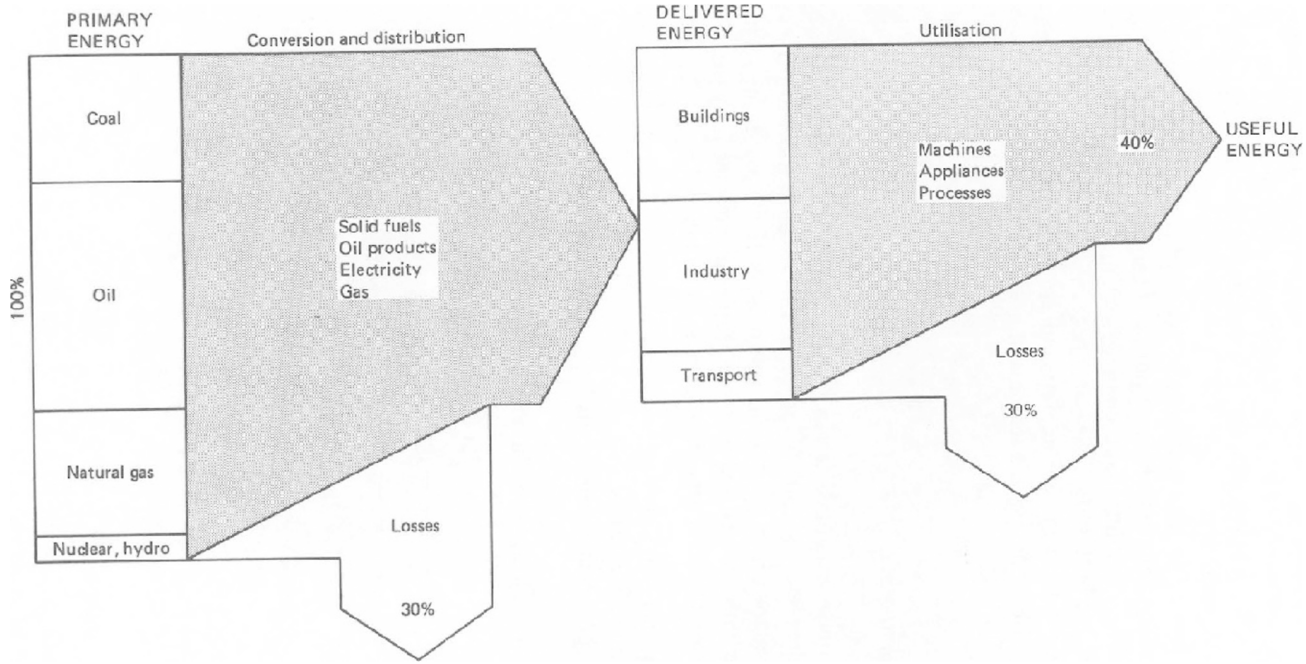


FIGURE 3.5 *Energy utilisation in the United Kingdom*

Seasonal energy requirements

The energy requirement of a building at any particular time depends on the state of the heat losses and the heat gains at that time. These factors vary but, as described in the previous sections, it is useful to consider the total effect over a standard heating season.

It is important to note that the calculation of seasonal heat losses and gains assumes average temperature conditions and can *not* be used to predict the size of the heating or cooling plant required; such a prediction needs consideration of the coldest and hottest days. Seasonal heat calculations are, however, valid for calculating total energy consumption and can therefore be used to predict the quantity of fuel required in a season and how much it will cost.

* * * * *

Worked example 3.3

Over a heating season of 33 weeks the average rate of heat loss from a certain semi-detached house is 2500 W for the fabric loss and 1300 W for the ventilation loss. The windows have areas: 6 m^2 south-facing, 5 m^2 east-facing, 6 m^2 north-facing. The house is occupied by three people and cooking is by gas.

Use the values for seasonal heat gains given in tables 3.6 and 3.8 and calculate:

(a) the seasonal heat losses;
(b) the seasonal heat gains; and
(c) the seasonal heat requirements.

(a) Total rate of heat loss = fabric loss + ventilation loss

$$= 2500\ \text{W} + 1300\ \text{W}$$

$$= 3800\ \text{W}$$

Heat energy lost = rate of heat loss x time taken

$$= 3800\ \text{W} \times (33 \times 24 \times 7 \times 60 \times 60)\ \text{s}$$

$$= 7.5842\ 10^9\ \text{J}$$

$$= 75.842\ \text{GJ}$$

Seasonal heat loss = 75842 MJ

(b) Heat gains

Solar window gain (table 3.6)	MJ
south (680 MJ/m^2 x 6)	4080
east (410 MJ/m^2 x 5)	2050
north (250 MJ/m^2 x 6)	1500

Casual gains (table 3.8)		
body heat (1000 MJ x 3)	3000	
cooking (gas)	6500	
water heating	2000	
electrical	3000	
	22130 MJ	

Seasonal heat gain = 22130 MJ

(c) Seasonal heat requirements = Heat loss − Heat gain

= 75842 − 22130 = 53712 MJ

= **53.712 GJ**

*   *   *   *   *

Fuel use

The heat energy required for buildings is commonly obtained from fuels such as coal, gas and oil, even if the energy is delivered in the form of electricity. Each type of fuel must be converted to heat in an appropriate piece of equipment and the heat distributed as required. The amount of heat finally obtained depends upon the original heat content of the fuel and the efficiency of the system in converting and distributing this heat.

Calorific value is a measure of the primary heat energy content of a fuel expressed in terms of unit mass or volume. Some typical calorific values are quoted in table 3.9. These values may be used to predict the quantity of fuel required and its price.

TABLE 3.9 *Calorific values of fuels*

Fuel	Calorific value
Coal, anthracite	35 MJ/kg
Coke	28 MJ/kg
Oil, domestic heating	45 MJ/kg
Gas, natural	38 MJ/m^3
Electricity	3.6 MJ/kWh

The overall efficiency of a system depends upon how much of the heat is extracted from the fuel, how much heat is lost through the flue and how much heat is lost in the distribution system. The *house efficiency* is an approximate figure for domestic systems that takes all these effects into account. Some typical values are quoted in table 3.10.

TABLE 3.10 *Domestic heating efficiencies*

Type of system	House efficiency*
Central heating (gas, oil, solid fuel)	60–70 per cent
Gas radiant heater	50–60 per cent
Gas convector heater	60–70 per cent
Electric fire	100 per cent

* Although the efficiency of an electrical heating appliance is 100 per cent to the consumer, the overall efficiency of the generation and distribution system is about 30 per cent.

* * * * *

Worked example 3.4

The seasonal heat requirement of a house is 54 GJ, which is to be supplied by a heating system with an overall house efficiency of 67 per cent. The solid fuel used has a calorific value of 31 MJ/kg. Calculate the mass of fuel required for one heating season.

$$\text{Efficiency} = \frac{67}{100}, \quad \text{Output energy} = 54\ \text{GJ}, \quad \text{Input energy} = ?$$

Using

$$\text{Efficiency} = \frac{\text{Output energy}}{\text{Input energy}}$$

$$\frac{67}{100} = \frac{54}{\text{Input energy}}$$

$$\text{Input energy} = 54 \times \frac{100}{67} = 80.597\ \text{GJ}$$

$$= 80597\ \text{MJ}$$

$$\text{Mass of fuel needed} = \frac{\text{Energy required}}{\text{Calorific value}}$$

$$= \frac{80597\ \text{MJ}}{31\ \text{MJ/kg}} = 2599.9$$

$$= \mathbf{2600\ kg}$$

* * * * *

Energy conservation

At present, most of the energy used to heat buildings, including electrical energy, comes from fossil fuels. It is energy that originally came from the Sun and produced plant growth. Then, because of changes in the Earth's geology, those ancient forests eventually became a coal seam or an oil field. The existing stocks of fossil fuels on Earth can not be replaced and, if consumption of them continues at the present rate, they will soon run out.

It will be difficult to do without oil and coal for some purposes, such as using them for raw materials in the chemical industry. But it is not essential to use fossil fuels for the heating of buildings. There are alternative energy sources available and the energy consumption of buildings can be greatly reduced by changes in the design and materials of buildings.

It has been estimated that, in the United Kingdom, some 40 to 50 per cent of the national consumption of primary energy is used for building services – such as heating, lighting and electricity. Over half of this energy is consumed in the domestic sector and most of that energy is used for space heating.

Methods of conserving energy in buildings are influenced by the costs involved and, in turn, these costs vary with the types of building and the current economic conditions. Some of the important options for future energy conservation in buildings are outlined below; articles in newspapers and journals are a help in staying informed of the balance and interactions of these matters.

(1) *Improved Energy Efficiency* Although electrical appliances have a high energy efficiency at the point of use, the overall efficiency of the electrical system is greatly reduced by inefficiencies at the power stations which are difficult to improve. Total savings in national energy are made if space heating is supplied by burning fossil fuels, such as coal or gas, inside the building heated. In some situations it may be possible to use waste heat from power stations for the heating of buildings in district heating schemes.

Household boilers, electric lamps and other appliances can be improved in efficiency and use can be made of new techniques. Heat pumps, for instance, make use of low temperature heat sources which are usually ignored.

(2) *Thermal Insulation* Assuming that new buildings in the future are built to high standards of thermal insulation, then the insulation of existing buildings can be upgraded. Roof insulation, cavity fill, double-glazing, internal wall-lining, exterior wall-cladding are techniques for consideration. The energy savings in improved thermal insulation may not always appear in full as some consumers, especially those with a poor standard of heating, enjoy higher temperatures.

(3) *Ventilation Heat* Lower ventilation rates reduce the quantity of heat lost in discarded air. This reduction can be achieved by the installation of controlled air conditioning, better seals in construction, the use of air-sealed door lobbies.

Some of the heat contained in exhausted air may be recovered by the use of heat exchangers such as heat pumps.

(4) *Natural Energy Sources* All buildings gain some casual heat from the Sun during winter but more of the available solar energy can be used if solar collectors are installed. In some countries the solar energy collected can be considerable but the latitude and the weather of the United Kingdom have, so far, tended to restrict the application of solar panels to supplementary hot water heating.

Other devices can extract natural energy from the wind, from ocean waves, from ocean temperature gradients, from the geothermal heat of the Earth's crust, and from plant growth.

EXERCISES

1 The external wall of a room measures 4.8 m by 2.6 m and has an average *U*-value 1.8 W/m^2 °C. The internal air temperature is 21 °C, the mean radiant temperature is 18 °C, and the external air temperature is 0 °C.
(a) Calculate the environmental temperature inside the room.
(b) Use the environmental temperature to calculate the rate of heat loss through the wall.

2 A house has a floor area of 92 m^2 and a ceiling height of 2.5 m. The average inside air temperature is kept at 18 °C, the outside air temperature is 6 °C and the average infiltration rate is 1.5 air changes per hour. The volumetric specific heat capacity of the air is 1300 J/m^3 °C.
(a) Calculate the rate of ventilation heat loss.
(b) Calculate the cost of the heat energy lost during 24 hours if the above conditions are maintained and replacement heat costs 2.5 pence per megajoule.

3 A sports pavillion has internal dimensions of 11 m x 4 m x 3 m high. 20 per cent of the wall area is glazed and the doors have a total area of 6 m^2. The *U*-values, in W/m^2 °C, are: walls 1.6, windows 5.5, doors 2.5, roof 1.5, floor 0.8. The inside air temperature is maintained at 18 °C when the outside air temperature is –2 °C. There are 4 air changes per hour and the volumetric specific heat capacity of air is 1300 J/m^3 °C. The heat gains total 2200 W.
(a) Calculate the net rate of heat loss from this building.
(b) Calculate the surface area of the radiators required to maintain the internal temperature under the above conditions. The output of the radiators is 440 W/m^2 of surface area.

4 A room has 7.5 m^2 area of single glazed windows, which have a *U*-value of 5.6 W/m^2 °C. It is proposed to double glaze the windows and reduce the *U*-value to 3.0 W/m^2 °C. During a 33 week heating season the average temperature difference across the windows is 7 °C.

(a) For both types of glazing, calculate the total heat lost during the heating season.
(b) Obtain current figures for the cost of electrical energy and the approximate cost of double glazing such windows. Estimate the number of years required for the annual fuel saving to pay for the cost of the double glazing.

5 The average rates of heat loss for a particular house are 1580 W total fabric loss and 870 W ventilation loss. The seasonal heat gains of the house total 27 500 MJ. The fuel used has a calorific value of 32 MJ/kg and the heating system has an overall efficiency of 75 per cent.
(a) Calculate the input heat required during a heating season of 33 weeks.
(b) Calculate the mass of fuel required to supply one season's heating.

ANSWERS

1 19 °C, 427 W
2 1495 W, 323 pence
3 8030 W, 18.25 m^2
4 5.868 GJ, 3.144 GJ
5 21.398 GJ, 892 kg

4 Humidity, Condensation, Refrigeration

This chapter is concerned with moisture in the air, condensation of moisture in buildings, and with refrigerators and heat pumps. These topics are part of the overall thermal study of buildings and they are all influenced by the properties of gases and vapours explained in chapter 1. The presence of water vapour in the air not only affects condensation, but also affects the human comfort conditions outlined in chapter 3.

HUMIDITY

Humidity is the study of moisture in the atmosphere. The maximum proportion of water vapour in air is about 5 per cent by weight yet this relatively small amount of moisture produces significant effects. Human comfort, condensation in buildings, weather conditions and water supplies are important environmental topics which are dependent on humidity. In addition, the durability of materials, the drying of materials, the operation of industrial processes, and the growth of plants are also affected by the amount of moisture in the air.

Most of the moisture in the atmosphere is a result of evaporation from the sea, which covers more than two-thirds of the Earth's surface. At any particular place natural humidity is dependent on local weather conditions and, inside a building, it is further affected by the thermal properties and the use of the building.

Water vapour

It was stated in chapter 1 that a vapour is a substance in the gas state, which can be liquefied by compression. If liquid water in a container is left open to the air then vapour forms in the space above. This process of evaporation occurs because some liquid molecules gain enough energy, from chance collisions with other molecules, to escape from the liquid surface and become gas molecules. The latent heat required for this change of state is taken from the other molecules of the liquid, which becomes cooled. The rate of evaporation increases if there is a movement of air above the liquid.

Water vapour is invisible. Steam and mist, which can be seen, are actually suspended droplets of liquid water. The molecules of water vapour rapidly occupy any given space and exert a vapour pressure on the sides of any surface that they are in contact with. This pressure behaves independently of the other gases in the air – an example of Dalton's Law of partial pressures.

Saturation

If the air space above a liquid is enclosed then the evaporated vapour molecules collect in the space and the vapour pressure increases. Some molecules are continually returning to the liquid state and eventually the number of molecules evaporating is equal to the number of molecules condensing. The air in the space is then said to be saturated. *Saturated air* is a sample which contains the maximum amount of water vapour possible at that temperature.

Vapour pressure increases as the amount of water vapour increases and at saturation the vapour pressure reaches a steady value called the saturated vapour pressure.

SATURATED VAPOUR PRESSURE (SVP) is the vapour pressure of the water vapour in an air sample that contains the maximum amount of vapour possible at that temperature.

Saturated vapour pressure is found to increase with increase in temperature. Table 4.1 lists the values for the saturated vapour pressure of water vapour at different temperatures.

TABLE 4.1 *Saturated vapour pressures of water vapour*

Temperature (°C)	SVP (Pa)	Temperature (°C)	SVP (Pa)
0	610	13	1497
1	657	14	1598
2	705	15	1704
3	758	16	1818
4	813	17	1937
5	872	18	2063
6	935	19	2197
7	1001	20	2337
8	1072	25	3166
9	1148	30	4242
10	1227	40	7375
11	1312	50	1234
12	1402	100	101 325

Increased vapour pressure indicates an increased moisture content, therefore the saturation of a fixed sample of air is delayed if the temperature of the air is raised. This property can be stated as an important general principle:

Warm air can hold more moisture than cold air.

If an unsaturated sample of moist air is cooled then, at a certain temperature, the sample will become saturated. If the sample is further cooled below this dew point temperature then some of the water vapour must condense to liquid. This may occur on surfaces, inside materials, or around dust particles in the form of cloud or fog.

Specification of humidity

Some of the properties of water vapour can be used to specify the amount of moisture in a sample of air. The different variables and their applications are listed below and described in the sections that follow:

1. moisture content;
2. vapour pressure;
3. dew point;
4. relative humidity.

Moisture Content Moisture content is a measure of absolute humidity – the actual quantity of water vapour present in the air.

$$\textbf{Moisture content} = \frac{\text{mass of water vapour in air sample}}{\text{mass of that air sample when dry}}$$

UNIT: kg/kg dry air (or g/kg).

Moisture content is not usually measured directly but it can be obtained from other types of measurement. Moisture content values are needed, for example, in determining what quantity of water an air-conditioning plant needs to add to or extract from a sample of air.

Vapour Pressure The molecules of water vapour in the air exert a pressure that increases as the amount of water vapour increases.

VAPOUR PRESSURE is the partial pressure exerted by the molecules of a vapour.

UNIT: pascal (Pa).

Older units: millibars (mb) where 1 mb = 101 Pa; mm of mercury where 1 mm = 133 Pa.

The vapour pressure of moisture in the air behaves independently of the other gases in the air. Values of vapour pressure are usually derived from other measurements and one of their uses is for determining the rate at which water vapour moves through materials.

Dew Point If moist air is cooled then, at a certain temperature, the air becomes saturated with water vapour. If this air is in contact with a surface that is at or below this temperature then a thin film of liquid will form – this is known as dew or condensation.

> **The DEW POINT is the *temperature* at which a fixed sample of air becomes saturated.**
>
> UNIT: °C or K.

A sample of air with a fixed moisture content has a constant dew point, even if the air temperature changes. The dew point is particularly relevant in the study of condensation in buildings. Dew point values can be measured directly or derived from other measurements.

Relative Humidity The relative humidity (RH) of a sample of air compares the actual amount of moisture in the air with the maximum amount of moisture the air can contain at that temperature. The strict definition of relative humidity is as follows

$$\textbf{Relative Humidity} = \frac{\text{Vapour pressure of sample}}{\text{SVP of sample at same temp}} \times 100$$

UNIT: per cent RH, at a specified temperature.

The vapour pressure of a sample varies in a similar manner to its moisture content for temperatures in the range 0 to 25 °C. So it is common to also describe relative humidity in terms of *percentage saturation* as follows

$$\text{Relative Humidity} = \frac{\text{mass of water vapour in air sample}}{\text{mass of water vapour required to saturate sample at same temperature}} \times 100$$

Another useful formula for relative humidity is:

$$\text{Relative Humidity} = \frac{\text{SVP at dew point}}{\text{SVP at room temperature}}$$

An RH of 100 per cent represents fully saturated air, as occurs in condensation on a cold surface or in a mist or fog. An RH of 0 per cent represents perfectly dry air; such a condition may be approached in some desert conditions and in sub-zero temperatures when water is frozen solid.

The SVP or saturated moisture content varies with temperature; therefore

RH changes as the temperature of the air changes. Despite this dependence on temperature, RH values are a good measurement of how humidity affects human comfort and drying processes.

Because warm air can hold more moisture than cool air, raising the temperature increases the SVP or the saturation moisture content. The denominator on the bottom line of the RH fraction then increases and so the RH value decreases. This gives rise to the following general effects on a sample of air

Heating the air – lowers the relative humidity.

Cooling the air – raises the relative humidity.

* * * * *

Worked example 4.1

A sample of air has an RH of 40 per cent at a temperature of 20 °C. Calculate the vapour pressure of this air (given: SVP of water vapour = 2340 Pa at 20 °C).

RH = 40 per cent, vp = ?, SVP = 2340 Pa

Using

$$RH = \frac{vp}{SVP} \times 100$$

$$40 = \frac{vp}{2340} \times 100$$

$$vp = \frac{2340 \times 40}{100} = 936$$

Vapour pressure = **936 Pa**

* * * * *

Hygrometers

Hygrometry – also called psychrometry – is the measurement of humidity. Hygrometers, or psychrometers, are instruments which measure the humidity of air. The absolute humidity (moisture content) of a sample of air could be measured by carefully weighing and drying it in a laboratory. Usually however, other properties of the air are measured and these properties are then used to calculate the value of the RH.

The *hair hygrometer* and the *paper hygrometer* make use of the fact that animal hair or paper change their dimensions with changes in moisture content. They can be made to give a direct reading of RH but they need calibration from another instrument.

Dew Point Hygrometer The temperature of the dew point is a property that can be observed and measured by cooling a surface until water vapour condenses upon it. The dew point temperature and the room temperature can then be used to obtain an RH value from tables or charts.

Regnault's Hygrometer is one form of dew-point hygrometer. A gentle passage of air is bubbled through liquid ether in a container and causes the ether to evaporate. The latent heat required for this evaporation is taken from the liquid ether and from the air immediately surrounding the container, which therefore becomes cooled. The polished outside surface of the container is observed and the moment a thin film of mist appears the temperature is noted from the thermometer in the ether. With careful use of the instrument this temperature is also the dew point temperature of the surrounding air.

Wet-and-dry-bulb Hygrometer If the bulb of a thermometer is wrapped in a wetted fabric the evaporation of the moisture absorbs latent heat and will cool the bulb. This wet bulb thermometer will record a lower temperature than an adjacent dry bulb thermometer (an ordinary thermometer). Dry air with a low RH causes rapid evaporation and produces a greater *wet bulb depression* than moist air. Saturated air at 100 per cent RH causes no net evaporation and the dry bulb and wet bulb thermometers then record the same temperature.

The two thermometers are mounted side by side, a water supply and fabric wick are connected to the wet bulb. The whirling sling hygrometer, shown in figure 4.1, is rapidly rotated by means of a handle before reading, to circulate fresh air around the bulbs. Each type of hygrometer has calibrated tables which give the RH value for a particular pair of wet and dry bulb temperatures.

Psychrometric chart

The different variables used so specify the amount of water vapour in the air are related to one another. These relationships between different types of measurement can be expressed in the form of tables of values, or in the form of graphs.

> **A PSYCHROMETRIC CHART is a set of graphs which are combined so that they plot the relationships between the different variables used to specify humidity.**

Figure 4.2 is one form of psychrometric chart, which displays the following measurements:

1. *Dry-bulb* temperature, the ordinary air temperature, is read from a horizontal scale on the base line.
2. *Moisture content*, or mixing ratio, is read from one of the right-hand vertical scales.

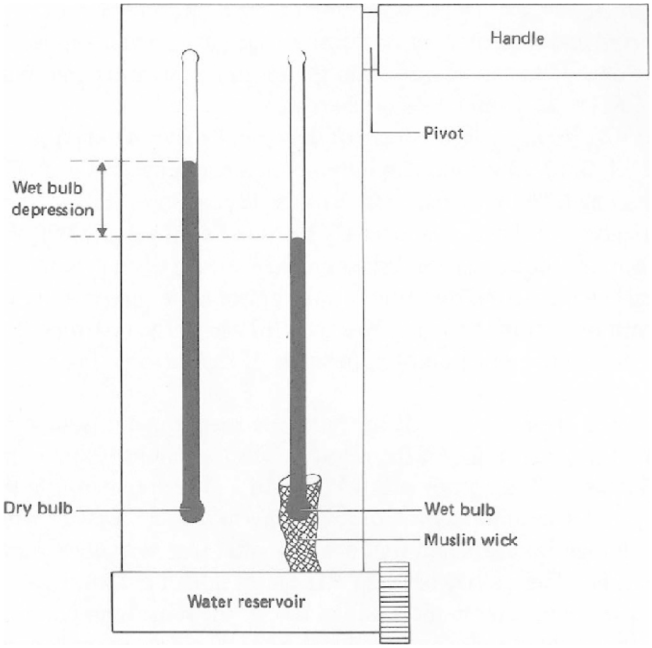


FIGURE 4.1 *Whirling sling hygrometer*

3. *Vapour pressure* of the air is read from one of the right-hand vertical scales.
4. *Wet-bulb* temperature is read from the sloping straight lines running from the saturation line.
5. *Dew-point* temperature is read from the horizontal lines running from the saturation line.
6. *Relative humidity* is read from the series of curves running from the left-hand vertical scale.

Notice that the saturation curve represents 100 per cent RH and at this condition the dry-bulb, wet-bulb and dew-point temperatures have the same value.

A psychrometric chart is strictly valid for one value of atmospheric pressure, the sea level pressure of 101.3 kPa being a common standard. Some versions of the psychrometric chart contain additional information, such as sensible and latent heat contents which are of particular use to heating engineers.

How to use the Chart In general, the amount of moisture in a particular sample of air is described by a pair of values, which also specify one point on the chart. Moving to any other point on the chart represents a change in the condition of the air and the type of change depends on the direction of movement on the chart.

For example, the following air conditions and changes are marked on figure 4.2.

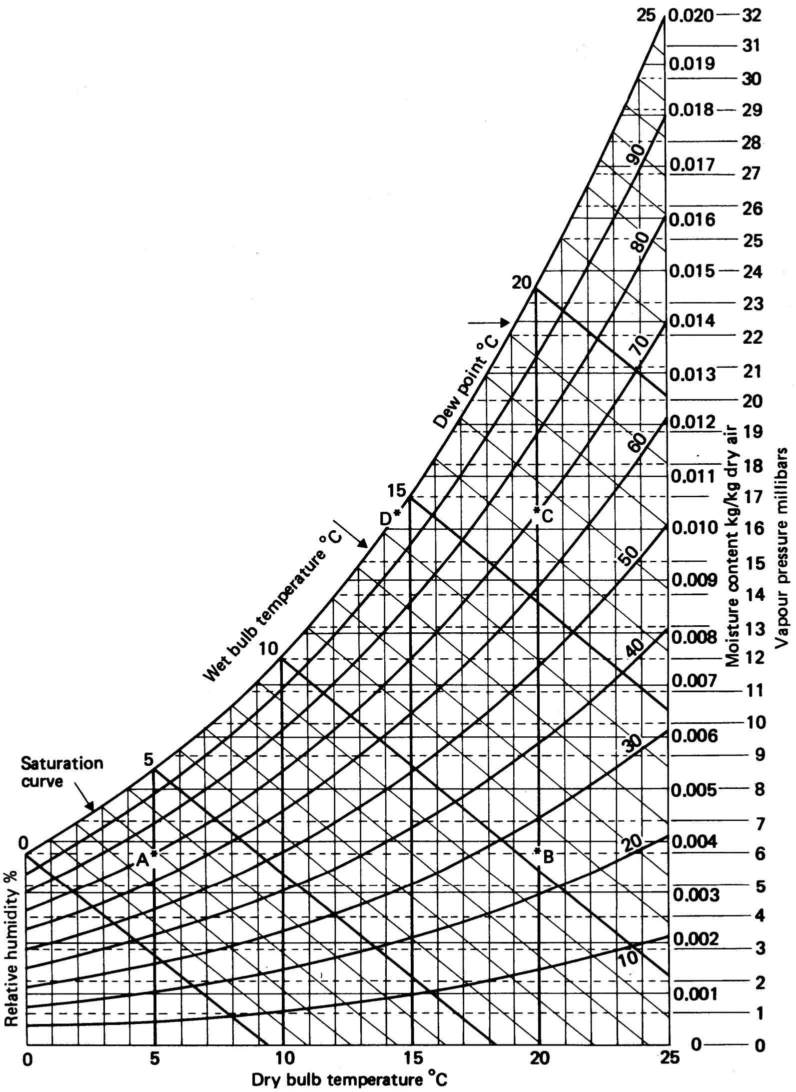


FIGURE 4.2 *Psychrometric chart of moisture and temperature*

Point A Represents air of 5 °C and 70 per cent RH. From the scales it can also be read that the moisture content is 0.0038 kg/kg and the vapour pressure is 6 mb.

Point B Represents air where the dry bulb has been raised to 20 °C and so the RH has decreased to 25 per cent. The moisture content and the vapour pressure are unchanged.

Point C Represents air at the same dry bulb but with an increase in moisture

content to 0.103 kg/kg. The vapour pressure has also increased. The RH has been restored to 70 per cent. The wet bulb at this state is 16.5 °C.
Point D Represents the dew point of this air: 14.5 °C. This is the temperature at which this air is saturated and has 100 per cent RH.

* * * * *

Worked example 4.2

External air at 0 °C and 80 per cent RH is heated to 18 °C. Use the psychrometric chart to determine:
(a) the RH of the heated air;
(b) the RH of the heated air if 0.005 kg/kg of moisture is added; and
(c) the temperature at which this moistened air would first condense.

Initial conditions: dry bulb = 0 °C, RH = 80 per cent, so moisture content = 0.003 kg/kg

(a) Heated air

moisture content = 0.003 kg/kg

dry bulb = 18 °C

so

RH = **23 per cent**

(b) Moistened air

moisture content = 0.003 + 0.005 = 0.008 kg/kg

dry bulb = 18 °C

so

RH = **62 per cent**

(c) For condensation

RH = 100 per cent

moisture content = 0.008

so

dew point = **10.8 °C gives condensation**

* * * * *

CONDENSATION IN BUILDINGS

Condensation in buildings is a form of dampness caused by water vapour in the air. Among the effects of condensation are misting of windows, beads of water on non-absorbent surfaces, dampness of absorbent materials and mould growth.

Condensation is not likely to be a problem in a building where it has been anticipated and designed for, as in a tiled bathroom or at an indoor swimming pool. Unwanted condensation, however, is a problem when it causes unhealthy conditions; damage to materials, to structures and to decorations; or general concern to people.

Condensation as a problem is a relatively recent concern and one that has been increasing. It is affected by the design of modern buildings and by the way in which buildings are heated, ventilated, and occupied. These factors will be considered in the sections on the causes of condensation and the remedies for it.

Principles of condensation

Warm air can hold more moisture than cold air. If air in a building acquires additional moisture this increased moisture content will not be apparent in places where the air is also warmed. But if this moist air comes into contact with colder air, or with a cold surface, then the air is likely to be cooled to its dew point. At this temperature the sample of air becomes saturated, it can no longer contain the same amount of water vapour as before, and the excess water vapour condenses to liquid. As a general principle it can be stated that

> **Condensation in buildings occurs whenever warm moist air meets surfaces that are at or are below the dew point of that air.**

It is convenient to classify the effects of condensation into two main types:

1. surface condensation;
2. interstitial condensation.

Surface Condensation Surface condensation occurs on the surfaces of the walls, windows, ceilings and floors. The condensation appears as a film of moisture or as beads of water on the surface and is most obvious on the harder, more impervious surfaces. An absorbent surface may not show condensation at first, although persistent condensation will eventually cause dampness.

Interstitial Condensation Interstitial condensation occurs within the construction of a building as indicated in figure 4.3. Most building materials are, to some extent, permeable to water vapour (that is, they allow the passage of air containing moisture). If this air cools as it passes through the structure then,

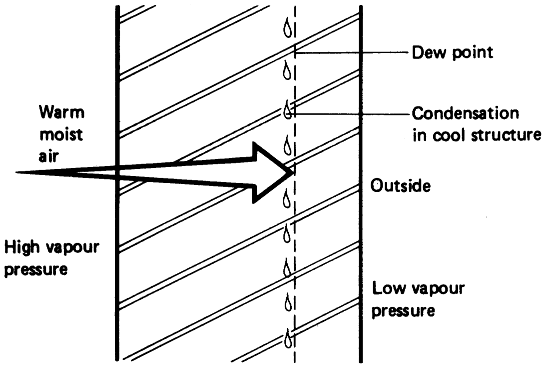


FIGURE 4.3 *Interstitial condensation*

at the dew point temperature, condensation will begin to occur inside the structure. The dampness caused by this interstitial condensation can damage important structural materials, such as steelwork, and can make insulating materials less effective.

Causes of condensation

The general requirements for condensation are moist air and cold surfaces. The factors that control the production of condensation can be conveniently grouped under the following headings:

1. moisture sources;
2. air temperatures;
3. structural temperatures;
4. ventilation;
5. use of buildings.

Moisture Sources The moisture present in any sample of air comes from a source of water. Local weather conditions determine the initial moisture state of the air but if the outside air is cool then it has a low moisture content and does not cause condensation when it is inside a building. Warm humid weather can cause condensation, especially if there is a sudden change from cool weather to warm moist conditions and the room surfaces are slow to heat up. In temperate climates like Britain the amount of rainfall does not have a big influence on condensation inside buildings.

Most of the moisture content of the air inside dwellings comes from the occupants and their activities. An average family produces about 12 kg of water vapour a day by the activities of normal breathing, cooking and washing. Flueless devices, such as gas cookers or paraffin oil heaters release much water vapour and increase the risk of condensation. The moisture produced in kitchens and bathrooms can quickly diffuse into other rooms and cause condensation far away from the original source of the moisture.

The construction processes involved in an average brick house add about 5000 kg of water to the structure – mainly by the water used for mixing concrete, mortar and plaster, and by exposure to weather. This water dries out during the first months of occupancy and adds to the moisture content of the air inside the building.

Temperatures Warm air can hold more moisture than cool air and is therefore less likely to cause condensation, but the extra moisture contained in the warm air can cause condensation when that air is cooled. For example, the kitchen itself may be warm enough to be free from condensation but the same moisturised air may cause condensation when it diffuses to a cooler part of the house.

Condensation occurs on those surfaces, or in those materials, that have a temperature at or below the dew point of the moist air. If moisture is progressively added to the air in a room then condensation will first occur on the coldest surfaces, on windows and cold pipes for example. The temperatures of room surfaces are lowest where the thermal insulation is lowest. Condensation can indicate the areas of worst insulation, particularly those caused by 'cold bridges' such as on lintels above windows.

The speed at which structures change their temperature affects condensation. Heavyweight construction, with a high thermal capacity, will be slower to respond to heating than a lightweight construction. A brick wall or a concrete floor, for example, is slow to increase its temperature when heated and condensation may occur for a period while it is heating. The positioning of insulation on the inside of heavyweight structures will allow the surface temperatures to rise more rapidly.

Ventilation The air outside a building usually has a much lower moisture content than the air inside. Ventilating a building therefore lowers the moisture content inside and reduces the risk of condensation. It is theoretically possible to avoid all condensation by adequate ventilation but as the ventilation rate increases the heat loss in the discarded air also increases.

The natural ventilation rates in dwellings have been decreasing over the years and this fact greatly contributes to the incidence of condensation in buildings. Chimneys have been eliminated in many modern houses and blocked-up in older houses. The construction of modern doors, windows, and floors usually provide better seals against the entry of outside air than in the past. As a result, the natural ventilation in dwellings has fallen from typical rates of 4 air changes per hour to less than 1 air change per hour.

Even with higher ventilation rates it is possible to have stagnant volumes of moist air where condensation still occurs; behind furniture and inside wardrobes, for example.

Use of Buildings There have been changes in the design of buildings and changes in the way we live in these buildings. These changes have tended to increase the risk of condensation.

Methods of heating buildings have changed and, at the same time, people expect higher standards of thermal comfort and cleanliness than they did in the past. The presence of chimneys in older houses aided natural ventilation and the use of a fire increased the ventilation by drawing air for combustion. The cool draughts that resulted were offset to some extent by the direct warming effect of radiant heat from the fire. Thermal comfort by means of warm air from modern convective heating requires low levels of air movement and this leads to the draught-proofing of houses. Public campaigns for better thermal insulation also encourage lower ventilation rates but, unfortunately, this tends to increase the risk of condensation.

Moisture-making activities such as personal bathing and washing of laundry have increased because of improved facilities and changing social customs. The laundry is often dried inside the building, sometimes by a tumble drier which is not vented to the outside.

Many dwellings are only occupied during the evening and the night. This pattern of living tends to compress the cooking and washing activities of a household into a short period, at a time when windows are unlikely to be opened. During the day, when the dwelling is unoccupied, the windows may be left closed for security reasons and heating is turned off, allowing the structure to cool.

Remedies for condensation

The preceding discussions of the causes of condensation also imply methods for helping to prevent it. They can be summarised as three main types of remedy for persistent condensation inside buildings.

1. ventilation;
2. heating;
3. insulation.

A combination of these three remedies is usually necessary. The use of vapour barriers as a measure against interstitial condensation is discussed under a separate heading. *Anti-condensation paint* can be useful for absorbing temporary condensation but it is not a permanent remedy for condensation.

Ventilation Ventilation helps to remove the moist air, which might otherwise condense if it is cooled inside the building. The ventilation is most effective if it is used near the source of moisture (for example, an extractor fan in the kitchen). Care should be taken that natural ventilation from windows does not blow steam into other rooms; kitchen and bathroom doors should be self-closing.

Some windows in each room should have a ventilator, which can give a small controlled rate of ventilation without loss of security, loss of comfort, or loss of significant amounts of heat energy. The cost of the heat lost in necessary ventilation is small and it should decrease as techniques of heat recovery from exhaust air are applied to houses.

Heating Heating a building raises the temperature of the room surfaces and helps keep them above the dew point of the air inside the building. Heated air also has the ability to hold more moisture, which can then be removed by ventilation before it has a chance to condense upon a cold surface.

The level and timing of the heating used in a building affects condensation and, in general, long periods of low heating are better than short periods at high temperature. Heavyweight construction, such as concrete and brickwork, should not be allowed to completely cool, and a continuous level of background heating helps prevent this. Heating devices without flues should not be used if there is a risk of condensation. A paraffin heater, for example, gives off about 1 litre of water for each litre of fuel used.

Insulation Thermal insulation reduces the rate at which heat is lost through a structure and will help in keeping inside surfaces warm, although insulation by itself cannot keep a room warm if no heat is supplied. Insulation placed on the inside surface of a heavyweight construction, such as a brick wall, helps to raise the surface temperature more quickly when the room is heated. With the insulation on the inside the outer part of the wall will remain cool and a vapour barrier may then be needed to prevent interstitial condensation.

CONDENSATION CONDITIONS

The risk of condensation occurring on or in a building material depends upon the temperature and the humidity of the air on both sides of the structure and also upon the resistance of the material to the passage of heat and vapour. The thermal resistance of materials was used to calculate *U*-values in chapter 2. This section introduces the similar idea of vapour resistance and uses it to calculate when and where condensation may occur in a structure.

Vapour transfer

The vapour pressure of a sample of air increases when the moisture content increases. Because the occupants of a building and their activities add moisture to the air, the vapour pressure of the inside air is therefore greater than that of the outside air. This pressure difference will tend to force water vapour through a structure from the inside to the outside.

The flow of water vapour through a structure depends upon the *permeability* of the various building materials present (that is, the ease with which they permit the diffusion of water vapour). This permeability of materials to water vapour can be expressed in a number of ways.

VAPOUR RESISTIVITY (r_V) is a measure of the resistance to the flow of vapour offered by unit thickness of a particular material.

UNIT: MN s/g m.

This property of a material is sometimes alternatively expressed as a *vapour diffusivity* or *vapour permeability* value, which is the reciprocal of vapour resistivity.

Table 4.2 lists typical values for the vapour resistivity of various building materials.

TABLE 4.2 *Vapour transfer properties of materials**

Material	Vapour resistivity (MN s/g m)
Brickwork	25–100
Concrete	30–100
Fibre insulating board	15–16
Hardboard	450–750
Mineral wool	5
Plaster	60
Plasterboard	45–60
Plastics	
expanded polystyrene	100–600
foamed polyurethane	30–1000
foamed urea-formaldehyde	20–30
Plywood	1500–6000
Timber	45–75
Stone	150–450
Strawboard, compressed	45–75
Wood wool	15–40
Membrane	*Vapour resistance* (MN s/g)
Aluminium foil	4000
Bituminised paper	11
Polythene sheet (0.06 mm)	110–120
Paint gloss	7.5–40
Vinyl wallpaper	5–10

* Adapted from *BRE Digest 110.*

Vapour resistance (R_v) is used to describe the resistance of a specific thickness of material and is given by the formula:

$$R_v = r_v L$$

where

R_v = vapour resistance of that material (MN s/g)

L = thickness of the material (m)

r_v = vapour resistivity of the material (MN s/g m)

A vapour resistance value is usually quoted for thin membranes, such as aluminium foil or polythene sheet, and some typical figures are given in table 4.2.

Total vapour resistance (R_{vT}) of a compound structure is the sum of the vapour resistance of all the separate components.

$$R_{vT} = R_{v1} + R_{v2} + R_{v3} + \ldots \text{etc}$$

Dew-point gradients

The changes in temperature inside a structure such as a wall were calculated in chapter 2. The temperature change across any particular component is given by the formula:

$$\Delta\theta = \frac{\Delta R}{R_T} \times \theta_T$$

where

$\Delta\theta$ = temperature drop across a particular layer

ΔR = thermal resistance of that layer

θ_T = total temperature drop across the structure

R_T = total thermal resistance of the structure

The temperature drop across each component can be plotted on to a scaled drawing of the structure to produce the temperature gradients, as shown in figure 4.4.

The *vapour pressure* drop across a component can be obtained in a similar manner from the formula:

$$\Delta P = \frac{\Delta R_v}{R_{vT}} \times P$$

where

ΔP = vapour pressure drop across a particular layer

ΔR_v = vapour resistance of that layer

P = total vapour pressure drop across the structure

R_{vT} = total vapour resistance of the structure

Vapour pressure changes can be plotted as gradients but they are usually used to produce a *dew-point gradient*. The dew point of each boundary in the structure is obtained from a psychrometric chart by using the corresponding structural temperature and vapour pressure.

* * * * *

Worked example 4.3

An external wall is constructed with an inside lining of plaster-board 10 mm, then expanded polystyrene board (EPS) 22 mm, then dense concrete 150 mm. The thermal resistances of the components, in m^2 °C/W, are: internal surface resistance 0.123, plasterboard 0.06, EPS 0.75, concrete 0.105, and external surface resistance 0.055. The vapour resistivities of the components, in MN s/g m, are: plasterboard 50, EPS 100, and concrete 30. The inside air is at 20 °C and 59 per cent RH; the outside air is at 0 °C and saturated. On a scaled cross section of the wall plot the structural temperature gradients and the dew-point gradients.

Step 1 Use thermal resistances to calculate the temperature drops across each layer and the temperature at each boundary. Tabulate the information.

Total temperature drop = 20 – 0 = 20 °C

Layer	Thermal resistance (m^2 °C/W)	Temperature drop $\left(\Delta\theta = \frac{\Delta R}{R} \times \theta_T\right)$	Boundary temperature (°C)
Internal surface	0.123	$\frac{0.123}{1.093} \times 20 = 2.3$	20
Plaster	0.06	$\frac{0.06}{1.093} \times 20 = 1.1$	17.7
EPS	0.75	$\frac{0.75}{1.093} \times 20 = 13.7$	16.6
Concrete	0.105	$\frac{0.105}{1.093} \times 20 = 1.9$	2.9
External surface	0.055	$\frac{0.055}{1.093} \times 20 = 1.0$	1.0
	$R = 1.093$		0.0

Step 2 Plot the boundary temperatures on a scaled section of the wall and join the points to produce temperature gradients, as in figure 4.4 overleaf.

Step 3 Use vapour resistances to calculate the vapour pressure drops across each of the layers and, from the psychrometric chart, find the dew-point temperature at each boundary.

Inside vapour pressure = 1400 } from psychrometric chart
Outside vapour pressure = 600 }

Total vapour pressure drop = 800 Pa

Layer	Thickness L (m)	Vapour resistivity r_v	Vapour resistance $R_v = r_v L$	vp drop $\Delta P = \frac{R_v}{R_{vT}} \times P$	vp at boundary (Pa)	Dew pt at boundary
Internal surface		neg				
					1400	12 °C
Plaster	0.010	50	0.5	$\frac{0.5}{7.5} \times 800 = 53$		
					1347	11.5 °C
EPS	0.025	100	2.5	$\frac{2.5}{7.5} \times 800 = 267$		
					1080	7.4 °C
Concrete	0.150	30	4.5	$\frac{4.5}{7.5} \times 800 = 480$		
					600	0 °C
External surface		neg				
		R_{vT}	7.5			

Step 4 Plot the dew-point temperatures on the scaled, section diagram to produce dew-point gradients, as in figure 4.4.

* * * * *

Condensation risk

Condensation occurs on room surfaces, or on inside structures, if moist air meets a material that is at or below the dew-point temperature of that air. To predict whether condensation may occur it is necessary to specify the air conditions expected inside and outside the building. The air temperatures and the dew points at any particular position can then be calculated.

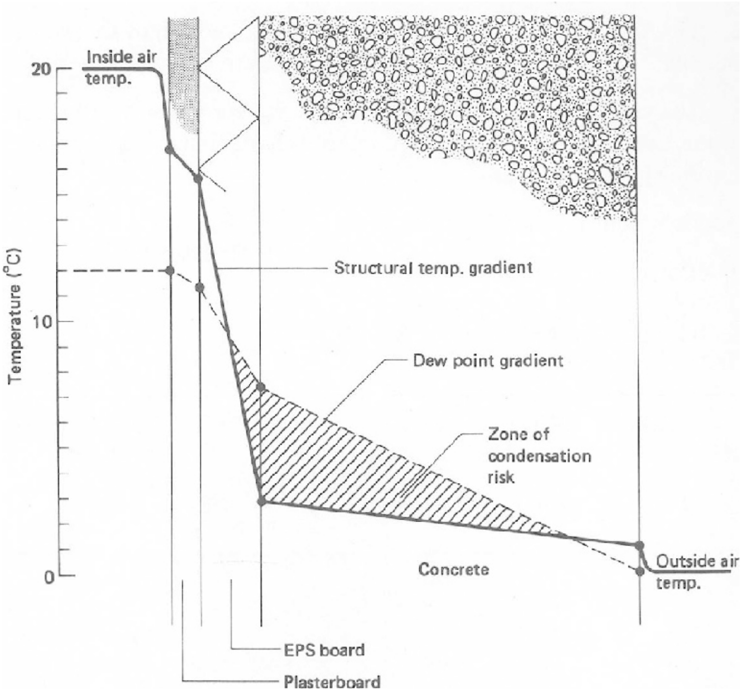


FIGURE 4.4 *Prediction of condensation*

Surface Condensation Alongside the surface of any partition in a building there is a layer of stationary air. The thermal resistance provided by this air layer – the internal surface resistance – causes the temperature of the surface to be lower than the air temperature in the room. Consequently, air coming into contact with the surface will be cooled and may condense on the surface.

The surface temperature can be calculated using the formula

$$\Delta T = \frac{\Delta R}{R} \times T$$

In Worked Example 4.3, for example, the surface temperature of 17.7 °C is above the dew point of 12 °C, so surface condensation would not occur under these conditions.

Interstitial Condensation If moist air is able to permeate through a structure from inside to outside then it is usually cooled and follows the gradient of structural temperature change. The dew-point temperature also falls and follows a gradient determined by the drop in vapour pressure across each material.

For specified air conditions, condensation will occur in any zone where the structural temperature gradient falls below the dew-point gradient. These zones can be predicted by scaled diagrams, such as figure 4.4 where condensation will occur in the EPS layer and in the concrete.

Vapour barriers

The risk of interstitial condensation in structures is reduced if moist air is discouraged from permeating through the materials of the structure.

A VAPOUR BARRIER is a layer of building material which has a high resistance to the passage of water vapour.

Vapour barriers, or vapour 'checks' can be broadly classified by the form in which they are applied:

(1) *Liquid films* Examples: bituminous solutions, rubberised or siliconised paints, gloss paints.
(2) *Pre-formed membranes* Examples: aluminium-foil board, polythene-backed board, polythene sheet, bituminous felt, vinyl paper.

The vapour resistance properties of some of these materials are given in table 4.2. Few materials will form a totally effective barrier to water vapour when installed in a construction because it is difficult to achieve complete seals at junctions, such as those between walls and ceilings. Also, barriers often have to be punctured by pipes and electrical fittings.

Vapour barriers need to be installed when there is a danger of interstitial condensation causing damage to the structure or to the insulation. Some interstitial condensation may be tolerated, such as in the outer brick leaf of a cavity wall.

Walls As a general rule vapour barriers should be installed on the warm side of the insulation layer; particularly if the insulation is on the inside of a wall. It is important that any water vapour inside the structure is able to escape and the outside surface should normally be permeable to water vapour, even though it may need to be weatherproof. Various materials and constructions can be waterproof but still allow water vapour to pass.

Roofs Roof cavities can suffer from severe condensation and appropriate ventilation and vapour barriers must be carefully provided. In general, if the insulation is at ceiling level then the roof will be a *cold roof* and a vapour barrier should be installed on the warm side of the insulation. As a further precaution the roof space, either flat or pitched, should be ventilated.

A *warm roof* has its thermal insulation placed immediately beneath the roof covering and then protected with a vapour barrier, as shown in figure 4.5. The roof deck is then kept near room temperature and any ceiling installed should

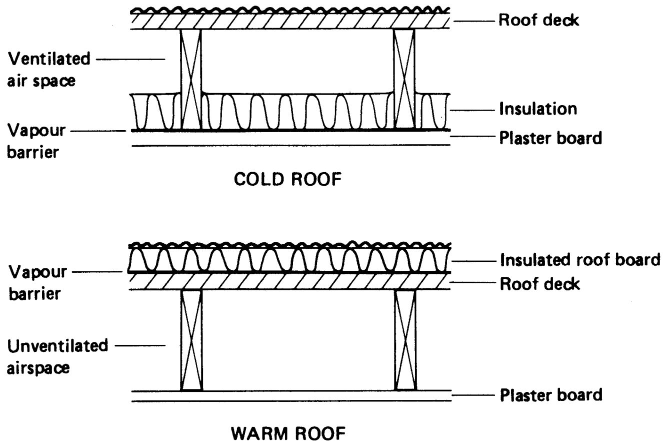


FIGURE 4.5 *Vapour barriers in roofs*

have minimum thermal insulation. Concrete flat roofs should always be built as warm roofs and if wet insulating screeds are used then permanent ventilation systems are essential. A vapour barrier should *not* be used under a wet screed.

REFRIGERATORS AND HEAT PUMPS

A refrigeration cycle causes heat energy to be transferred from a cooler region to a warmer region. This is against the natural direction of heat flow and can only be achieved by supplying energy to the cycle. This movement of heat can be used for cooling (as in a refrigerator) or for heating (as in a heat pump). A refrigeration cycle can also be the basis of a single plant capable of either heating or cooling a building, according to needs.

The refrigeration cycle

A refrigeration system operates by absorbing heat, transferring that heat elsewhere and then releasing it. The most common forms of refrigeration make use of two physical mechanisms that have already been described in chapter 1:

1. the latent heat changes that occur with changes of state; and
2. the behaviour of vapours when compressed and expanded.

A refrigeration system employs a volatile liquid called a refrigerant which undergoes the cycle described below and illustrated in figures 4.6 and 4.8:

Stage A The liquid refrigerant is allowed to evaporate. The latent heat required for the evaporation is extracted from the surroundings of the evaporator, which acts as a cooler.

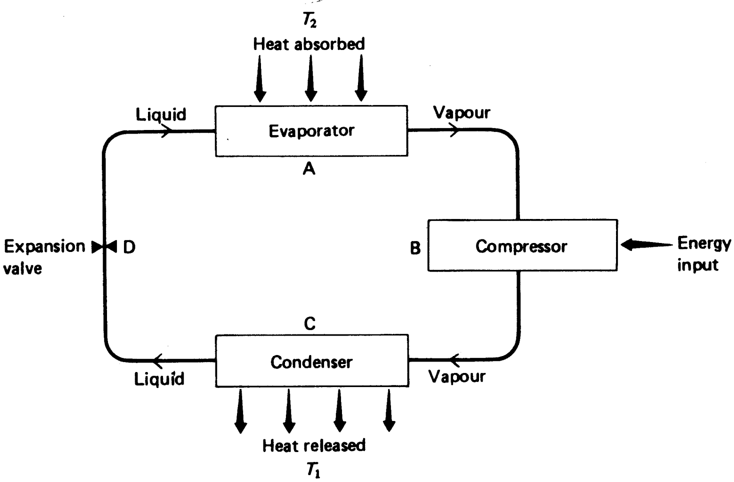


FIGURE 4.6 *Compression refrigerator and heat pump cycle*

Stage B The pressure of the refrigerant vapour is increased by means of a compressor or other mechanism. This pressurisation raises the temperature of the refrigerant and requires an input of energy into the system.
Stage C The refrigerant vapour condenses to liquid when it cools below its boiling point. The latent heat released is emitted by the condenser which acts as a heater.

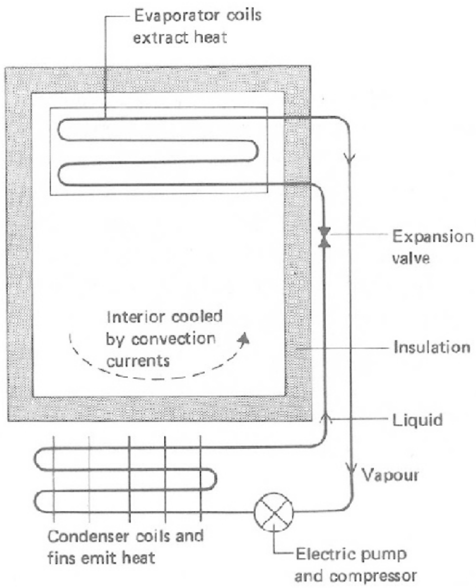


FIGURE 4.7 *Compression refrigerator layout*

Stage D The liquid refrigerant is passed through an expansion valve and its pressure drops. The refrigerant then evaporates and can repeat the cycle.

Refrigerants In order to undergo the above cycle a refrigerant must be below its critical temperature, or it will not liquefy; and it must be above its melting point, or else it will solidify. In general an ideal refrigerant should possess the following properties:

1. low boiling point;
2. high latent heat of vaporisation;
3. be easily liquefied by compression;
4. be stable, non-toxic and non-corrosive.

It is possible to use air or water as refrigerants but the more common substances employed are described below:

Freon is a mixture of organic compounds containing carbon, chlorine, and fluorine. It is available in various commercial variations and is widely used in refrigeration systems, including domestic refrigerators. It is colourless, non-flammable, non-toxic, and non-corrosive.

Ammonia (NH_3) is used in absorption refrigeration systems and in large plants. It is efficient but toxic if it leaks.

Carbon dioxide (CO_2) is used in some large refrigeration plants and requires high operating pressures.

Refrigerators

Compression Refrigeration Cycle The compression refrigeration cycle is driven by an electric compressor which also circulates the refrigerant. The operating principles of the compression cycle are shown schematically in figure 4.6.

A domestic refrigerator usually uses the compression cycle and a layout of a practical refrigerator is shown in figure 4.7. The evaporator coils are situated at the top of the compartment to where natural convection currents aid the flow of heat. The heat is extracted and transferred to the condenser coils which release the heat outside the refrigerator with the help of cooling fins. The temperature of the interior is regulated by a thermostat which switches the compressor motor on and off.

Absorption Refrigeration Cycle The absorption refrigeration cycle, shown in figure 4.8, operates without a compressor and needs no moving parts. The principle of evaporative cooling is the same as for the compression cycle but the driving mechanism is not as easy to explain.

The refrigerant is pressurised and circulated by a generator or 'boiler', which can be heated by any source. A concentrated solution of ammonia in water is heated by the generator and the ammonia is driven off as a vapour, leaving the water. The pressure of the ammonia vapour increases and it passes through the condenser and evaporator, so acting as a refrigerant. In the absorber the ammonia is redissolved by water flowing from the generator and the cycle repeats.

The absorption cycle is used in domestic gas-operated refrigerators and for commercial plants, particularly where there is a source of waste heat which can be used (see figure 4.8).

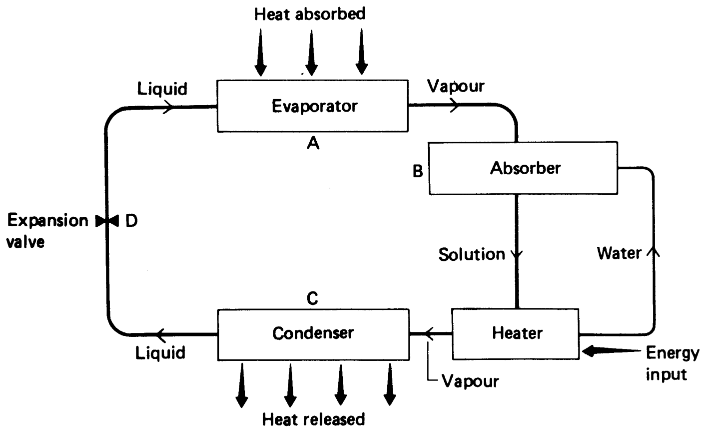


FIGURE 4.8 *Absorption refrigeration cycle*

Heat pumps

Every object in the environment is a potential source of heat, even ground that is frozen solid. The quantity and the temperature of this 'low grade' heat is usually too low for it to be useful. With some sources however, it can be profitable to 'pump' this heat to a higher temperature.

> **A HEAT PUMP is a device which extracts heat from a low temperature source and upgrades it to a higher temperature.**

The heat pump employs a standard refrigeration cycle and the compression system, shown in figure 4.6, is the commonest type:

Stage A The evaporator coils are placed in the low temperature heat source and heat is absorbed by the evaporating refrigerant.
Stage B The temperature of the refrigerant is increased as it is compressed, the extra energy being supplied by the electric motor.
Stage C The refrigerant condenses and releases heat energy at a useful temperature. The condenser coils are used to heat air or some other medium.
Stage D The refrigerant is expanded and it evaporates for a repeat of the cycle.

Efficiency The main feature of the heat pump is that it produces more usable energy than it consumes. This efficiency is measured by a coefficient of performance for heating.

The Coefficient of Performance (COP_H) of a heat pump is the ratio of heat output to the energy needed to operate the pump.

$$COP_H = \frac{\text{Heat energy output}}{\text{Pump energy input}} = \frac{T_1}{T_1 - T_2}$$

where

T_1 = absolute temperature of heat output (K),

T_2 = absolute temperature of heat source (K).

The above expressions show that the COP_H is always greater than unity, so that a heat pump always gives out more energy than is directly supplied to the pump. It therefore uses electricity more efficiently than any other system. The temperature equation also shows that the COP_H decreases as the temperature of the heat source decreases, which unfortunately means lower efficiency in colder weather.

The COP_H values achieved by heat pumps under practical conditions are between 2 and 3. These values take account of the extra energy needed to run circulatory fans and pumps, to defrost the heat extraction coils, and to supply supplementary heating if necessary.

Heat Sources The extraction coils (evaporator) of a heat pump should ideally be placed in a heat source which remains at a constant temperature.

Air is the most commonly used heat source but has the disadvantage of low thermal capacity. Outside air also has a variable temperature and when the air temperature falls the COP_H also falls. The exhaust air of a ventilation system is a useful source of heat at constant temperature.

The *ground* can be a useful source of low-grade heat in which to bury the extraction coils of a heat pump. Ground temperatures remain relatively constant but large areas may need to be used.

Water is a good heat source for heat pumps provided that the supply does not freeze under operating conditions. Rivers, lakes, the sea and supplies of waste water can be used.

EXERCISES

1 A sample of air at 10 °C has a vapour pressure of 540 Pa. Calculate the RH of this air, given that the SVP of water is 1230 Pa at 10 °C.

2 The air temperature in a room is 20 °C and the dew point is 15 °C. Calculate

the RH of this air, given that the SVP of water is 2340 Pa at 20 °C and 1700 Pa at 15 °C.

3 Use the psychrometric chart for the following:
(a) If air has a dry bulb temperature of 20 °C and a wet bulb temperature of 15 °C then find the RH and the dew point.
(b) If air at 16 °C dry bulb has an RH of 70 per cent then find the moisture content.
(c) If air at 20 °C dry bulb has a vapour pressure of 7 mb then find the RH.

4 External air at 4 °C and 80 per cent RH is heated to 20 °C. Use the psychrometric chart to find the following:
(a) The RH of the heated air.
(b) The RH of the heated air if 0.006 kg/kg of moisture is added.
(c) The increase in vapour pressure between the two states.

5 The surface of a wall has a temperature of 11 °C when air at 14 °C begins to condense upon the wall surface. Use the psychrometric chart to find:
(a) the RH of the air; and
(b) the reduction in moisture content necessary to lower the RH of the air to 50 per cent.

6 A 102 mm thick brick wall is insulated on the inside surface by the addition of 40 mm of mineral wool covered with 10 mm of plasterboard. The thermal resistances, in m^2 °C/W, are: external surface 0.055, brickwork 0.133, mineral wool 0.4, and internal surface 0.123. The vapour resistivities, in MN s/g m, are: brickwork 60, mineral wool 5, and plasterboard 50. The inside air is at 20 °C and 59 per cent RH; the outside air is at 0 °C and 100 per cent RH. Calculate the boundary values of structural temperatures and dew points. Plot a structural temperature profile and a dew point profile on the same scaled cross-section diagram of the wall. Comment on the results.

ANSWERS

1 44 per cent
2 72.6 per cent
3 (a) 58 per cent, 12 °C; (b) 0.008 kg/kg; (c) 30 per cent
4 (a) 27 per cent; (b) 68 per cent; (c) 9.6 mb
5 (a) 81 per cent; (b) 0.003 kg/kg

5 Principles of Light

Light and the effects of light are a major element in the human sense of environment. Both artificial and natural sources of light are used in buildings and these sources can be supplied and controlled in many ways. This chapter describes the nature of light, the effect of light upon the eye and the brain, and the measurement of light and lighting.

ELECTROMAGNETIC RADIATION

Light is energy in the form of electromagnetic radiation. This energy is radiated by processes in the atomic structure of different materials and causes a wide range of effects. The different forms of electromagnetic radiation all share the same properties of transmission although they behave quite differently when they interact with matter.

Light is that particular electromagnetic radiation which can be detected by the human sense of sight. The range of electromagnetic radiation to which the eye is sensitive is just a very narrow band in the total spectrum of electromagnetic emissions, as is indicated in figure 5.1.

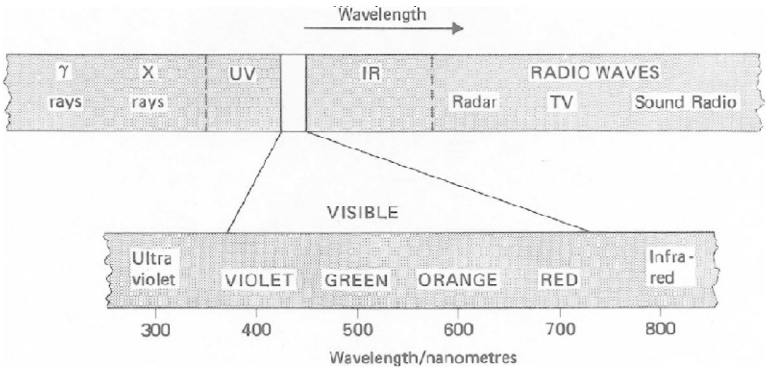


FIGURE 5.1 *Electromagnetic spectrum*

Electromagnetic waves

The transmission of light energy can be described as a wave motion or as 'packets' of energy called photons. The two theories co-exist in modern physics and are used to explain different effects. The most convenient theory for everyday effects is that of electromagnetic wave motion. This can be considered as having the following general properties:

1. The energy resides in fluctuations of electric and magnetic fields, which travel as a transverse wave motion.
2. These waves require no medium and can therefore travel through a vacuum.
3. Different types of electromagnetic radiation have different wavelengths or frequencies.
4. All electromagnetic waves have the same velocity, which is approximately 3×10^8 m/s in vacuo.
5. The waves travel in straight lines but can be affected by:

Reflection	Reversal of direction which occurs at a surface.
Refraction	Deflection which occurs at the boundaries of different materials.
Diffraction	Deflection which occurs at apertures or edges of objects.

Visible radiation

The wavelengths of electromagnetic radiation that are visible to the eye range from approximately 380 nm to 760 nm (1 nanometer (nm) is 10^{-9} metre). If all the wavelengths of light are seen at the same time the eye cannot distinguish the individual wavelengths and the brain has the sensation of white light.

WHITE LIGHT is the effect of combining all the wavelengths of light.

White light can be separated into its component wavelengths. One method is to use the different refractions of light that occur in a glass prism, as shown in figure 5.2. The result is a *spectrum* of light, which is traditionally described in

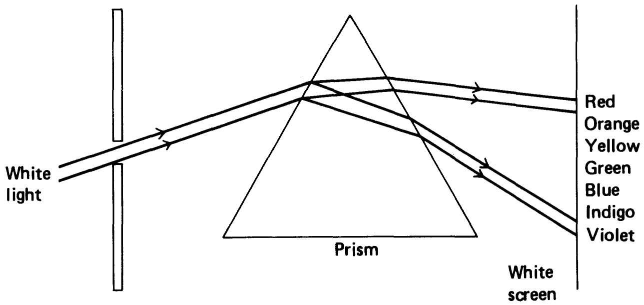


FIGURE 5.2 *Dispersion of white light*

the seven colours of the rainbow although, in fact, there is a continuous range of hues (colours) whose different wavelengths cause different sensations in the brain.

MONOCHROMATIC LIGHT is light of one particular wavelength and colour.

If the colours of the spectrum are recombined then white light is again produced. Varying the proportions of the individual colours can produce different qualities of 'white' light.

Non-visible radiation

Electromagnetic radiations with wavelengths outside the range of visible wavelengths cannot, by definition, be detected by the human eye. However, those radiations immediately adjacent to the visible range of wavelengths are emitted by the Sun, along with light, and are often relevant to lighting processes.

Infra-red Infra-red (i.r.) radiation has wavelengths slightly greater than those of red light and can be felt as heat radiation from the Sun and from other heated bodies. Infra-red radiation is made use of in radiant heating devices, for detecting patterns of heat emissions, for 'seeing' in the dark, and for communication links.

Ultra-violet Ultra-violet (u.v.) radiation has wavelengths slightly less than those of violet light. It is emitted by the sun and also by other very hot objects. Ultra-violet radiation helps keep the body healthy but excessive amounts can damage the skin and the eyes.

Ultra-violet radiation can be used to kill harmful bacteria in kitchens and in hospitals. Certain chemicals can convert u.v. energy to visible light and the effect is made use of in fluorescent lamps.

NATURE OF VISION

The portion of the electromagnetic spectrum known as light is of environmental interest to human beings because it activates their sense of sight, or vision. Vision is a sensation caused in the brain when light reaches the eye. The eye initially treats light in an optical manner producing a physical image in the same way as a camera. This image is then interpreted by the brain in a manner which is psychological as well as physical.

The eye

Figure 5.3 shows the main features of the human eye with regard to its optical properties. The convex lens focuses the light from a scene to produce an

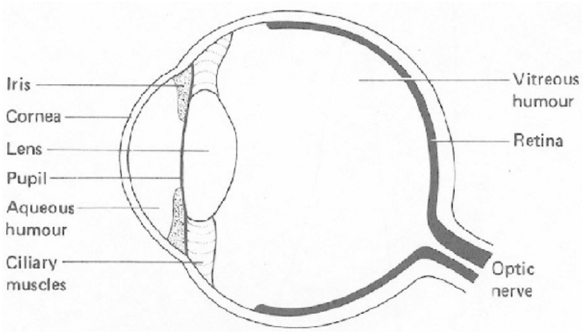


FIGURE 5.3 *Structure of the eye*

inverted image of the scene on the retina. When in the relaxed position the lens is focused on distant objects. To bring closer objects into focus the ciliary muscles increase the curvature of the lens; a process called *accommodation*. The closest distance at which objects can be focused, called the *near point*, tends to retreat with age as the lens become less elastic.

The amount of light entering the lens is controlled by the iris, a coloured ring of tissue, which automatically expands and contracts with the amount of light present. The retina, on which the image is focused, contains light receptors which are concentrated in a central area called the fovea, and which are deficient in another area called the blind spot.

Operation of vision

The light energy falling on the retina causes chemical changes in the receptors which then send electrical signals to the brain via the optic nerve. A large portion of the brain is dedicated to the processing of the information received from the eyes and the eyes are useless if this sight centre in the brain is damaged.

The initial information interpreted by the brain includes the brightness and colour of the image. The stereoscopic effect of two eyes gives further information about the size and position of objects. The brain controls selection of the many items in the field of view and the sense of vision greatly depends on interpretations of images learned from previous experience.

Sensitivity of vision

The light-sensitive receptors on the retina are of two types. They respond to different wavelengths of light in the manner shown in figure 5.4 and they give rise to two types of vision.

Cone Vision The cones are the light receptors that operate when the eye is adapted to normal levels of light. The spectrum appears coloured. There is a

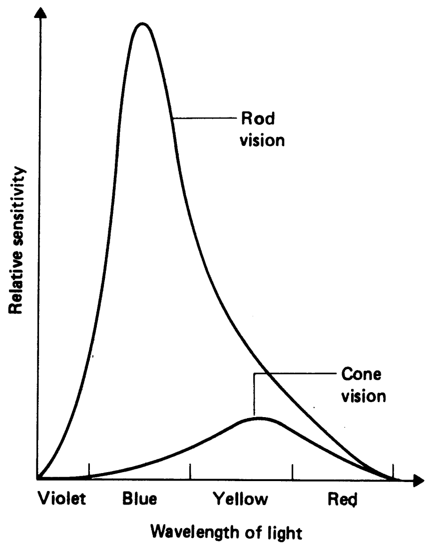


FIGURE 5.4 *Sensitivity of eye*

concentration of cones on the fovea at the centre of the retina and these are used for seeing details.

Rod Vision The rods are the light receptors that operate when the eye is adapted to very low levels of light. The rods are much more sensitive than the cones but the spectrum appears uncoloured. The colourless appearance of objects in moonlight or starlight is an example of this vision. There is a concentration of rods at the edges of the retina, which cause the eyes to be sensitive to movements at the boundary of the field of view.

Terminology of vision

Visual Field Visual field is the total extent in space that can be seen when looking in a given direction.

Visual Acuity Acuity is the ability to distinguish between details that are very close together. This ability increases as the amount of available light increases.

Adaption Adaption is the process occurring as the eyes adjust to the relative brightness or colour of objects in the visual field. The cones and the rods on the retina take a significant amount of time to reach full sensitivity.

Contrast Contrast is the difference in brightness or colours between two parts of the visual field.

MEASUREMENT OF LIGHTING

Light is one form of energy and could be measured by the standard units of energy, but the effect of light on the human environment also depends upon the sensitivity of the eye. Quantities of lighting are therefore measured by an independent set of units.

Solid angle

As light can radiate in all three dimensions it is necessary to measure the way in which the space around a point can be divided into 'solid angles'. The standard SI unit of solid angle is the steradian, illustrated in figure 5.5.

> **One Steradian (ω) is that solid angle at the centre of a sphere which cuts an area on the surface of the sphere equal to the size of the radius squared.**

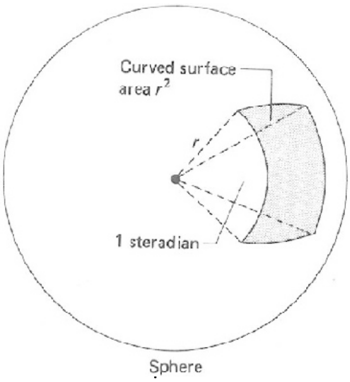


FIGURE 5.5 *The steradian*

Notice that the size of a solid angle does not depend upon the radius of the sphere or upon the shape of the solid angle. The total amount of solid angle contained around a point at the centre of a sphere is equal to the number of areas, each of size radius squared, which can fit onto the total surface area of a sphere. That is

$$\text{Total solid angle around a point} = \frac{\text{surface area at sphere}}{\text{area giving 1 steradian}} = \frac{4\pi r^2}{r^2}$$

$$= 4\pi$$

Therefore a complete sphere contains a total of 4π steradians.

Luminous intensity

To compare different light sources and measure their 'strength' the concept of luminous intensity is used.

LUMINOUS INTENSITY (I) is the power of a light source, or illuminated surface, to emit light in a particular direction.

UNIT: candela (cd).

The candela is one of the base units in the SI system. One candela is defined as the luminous intensity in a given direction of a source that emits monochromatic radiation of frequency 540 x 10^{12} Hz and of which the radiant intensity in that direction is 1/683 W/ω.

The effect of one candela is still approximately the same as the original idea of one candlepower and the *mean spherical intensity* (MSI) of a 100 W light bulb is about 100 cd.

Luminous flux

The rate of flow of any electromagnetic energy can be expressed in terms of power but light energy is also measured by luminous flux.

LUMINOUS FLUX (F) is the rate of flow of light energy.

UNIT: lumen (lm).

By definition, one lumen is the luminous flux emitted within one steradian by a point source of light of one candela, as shown in figure 5.6.

In general, luminous flux and luminous intensity are related by the formula

$$\boxed{I = \frac{F}{\omega}}$$

where

I = mean spherical intensity of the source (cd)

F = luminous flux emitted by the source (lm)

ω = solid angle containing the flux (sterad).

Consider a point source of 1 cd emitting flux in all directions. The total solid angle around a point is 4π steradians.

Using

$$F = I \times \omega$$

$= 1 \times 4\pi$

$= 4\pi$

So, the total flux emitted by a source of 1 cd is 4π lm.

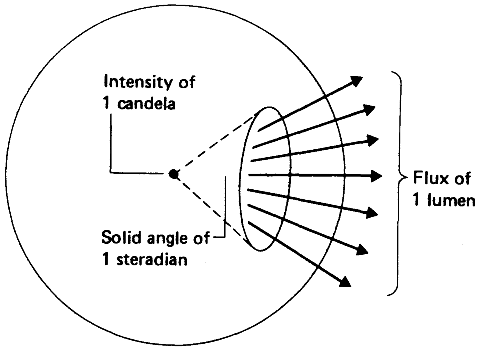


FIGURE 5.6 *Definition of the lumen*

Illuminance

When luminous flux falls on a surface it illuminates that surface. The effect of this illumination is termed illuminance.

ILLUMINANCE (E) is the density of luminous flux reaching a surface.

UNIT: lux (lx) where 1 lux = 1 lumen/(metre)^2.

Common illuminance levels range from 50 lux for low domestic lighting to 50 000 lux for bright sunlight. Recommended lighting levels are specified in terms of illuminance and examples of standards are given in the section on lighting design.

If light is falling onto a surface at right angles to the surface then the illuminance is given by the formula

$$E = \frac{F}{A}$$

where

E = illuminance on surface (lx)

F = total flux reaching surface (lm)

A = area of the surface (m^2)

* * * * *

Worked example 5.1

A small source of light has a mean spherical intensity of 100 cd. One quarter of the total flux emitted from the source falls at right angles onto a surface measuring 3 m by 0.7 m. Calculate:
(a) the total luminous flux given out by the source; and
(b) the illuminance produced on the surface.

(a) $I = 100$ cd, $\omega = 4\pi$, $F = ?$

Using $I = \dfrac{F}{\omega}$

$$100 = \frac{F}{4\pi}; \quad F = 4\pi \times 100 = 1256.64$$

Total flux = **1256.64 lm**

(b) $F = 1256.64 \times 0.25 = 314.16$ lm, $A = 0.7 \times 3 = 2.1\ \text{m}^2$, $E = ?$

Using $E = \dfrac{F}{A}$

$$= \frac{314.16}{2.1} = 149.6$$

Illuminance = **150 lx**

* * * * *

Inverse square law of illumination

As the luminous flux emitted by a point source of light travels away from the source the area over which the flux can spread increases. Therefore, the luminous flux per unit area (i.e. the illuminance), must decrease. This relationship is expressed by the inverse square law and is illustrated in figure 5.7.

Inverse Square Law

The illuminance produced by a point source of light decreases in inverse proportion to the square of the distance from the source.

In SI units this law may be expressed mathematically by the formula

$$\boxed{E = \frac{I}{d^2}}$$

where

I = intensity of a point source (cd)

d = distance between source and surface (m)

E = illuminance on that surface (lx)

An important consequence of the Inverse Square law is that changes in the position of light sources produce relatively large changes in lighting effect. For example, doubling the distance between a lamp and a surface causes the illuminance on that surface to decrease to one quarter of its original value.

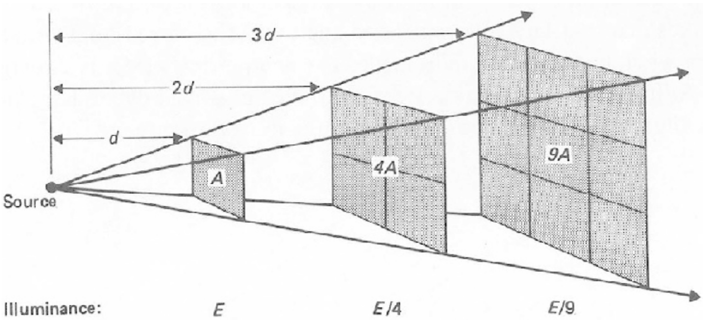


FIGURE 5.7 *Inverse square law of illumination*

* * * * *

Worked example 5.2

A lamp has a luminous intensity of 1200 cd and acts as a point source. Calculate the illuminance produced on surfaces: (a) at 2m; and (b) at 6 m distance from the lamp.

$I = 1200$ cd, $d_1 = 2$ m and $d_2 = 6$ m, $E = ?$

Using $E = \frac{I}{d^2}$

(a)

$$E = \frac{I}{{d_1}^2} = \frac{1200}{2^2} = 300$$

Illuminance = **300 lx** at 2 m

(b)

$$E = \frac{I}{d_2{}^2} = \frac{1200}{6^2} = 33.33$$

Illuminance = **33.33 lx** at 6 m

*   *   *   *   *

Cosine law of illumination

When the luminous flux from a point source reaches the surface of a surrounding sphere the direction of the light is always at right angles to that surface. However, light strikes many surfaces at an inclined angle and therefore illuminates a larger area than when it strikes at a right angle. The geometrical effect is shown in figure 5.8. If the luminous flux is kept constant but spread over a larger area then the illuminance at any point on that area must decrease.

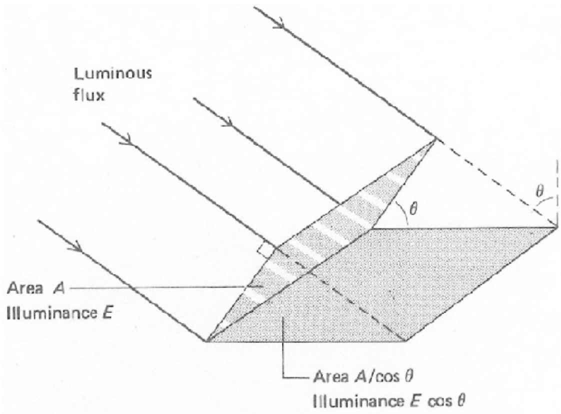


FIGURE 5.8 *Cosine law of illumination*

Figure 5.9 shows how the area illuminated increases by a factor of 1/cosine θ. Because illuminance is equal to luminous flux divided by area the illuminance decreases by a factor of cosine θ. This relationship is sometimes termed *Lambert's Cosine Rule* and can be expressed by a general formula combining the factors affecting illumination

$$\boxed{E = \frac{I}{d^2} \cos \theta}$$

where

E = illuminance on surface (lx)

I = intensity of source (cd)

d = distance between source and surface (m)

θ = angle between direction of flux and the normal

(Note: when $\theta = 0°$ then $\cos\theta = 1$.)

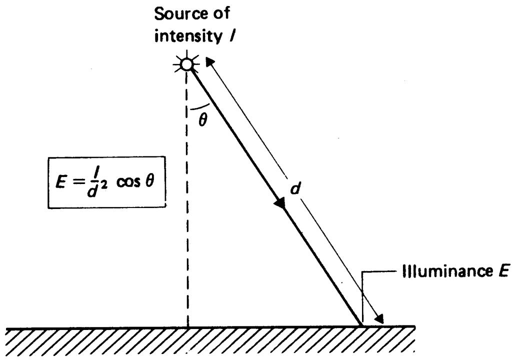


FIGURE 5.9 *Laws of illumination*

The Cosine Law affects most lighting arrangements as it is usually difficult for all surfaces to receive light at right angles. For example, when a light bulb on the ceiling illuminates a floor, only the point directly below the light fitting will receive luminous flux at right angles; the light will strike all other parts of the floor at varying angles of inclination. The radiation from the Sun strikes the surface of the Earth at different angles of incidence. The intensity of light and heat received at the ground varies in accordance with the cosine law and the effect is particularly noticeable at latitudes away from the Equator.

* * * * *

Worked example 5.3

A lamp acts as a point source with a mean spherical intensity of 1500 cd. It is fixed 2 m above the centre of a circular table which has a radius of 1.5 m. Calculate the illuminance provided at the edge of the table, ignoring reflected light.

$E = ?$, $I = 1500$ cd,

$d^2 = 2^2 + 1.5^2 = 4 + 2.25 = 6.25$; $d = 2.50$

$$\cos\theta = \frac{2}{d} = \frac{2}{2.5} = 0.8$$

Using

$$E = \frac{I}{d^2} \cos \theta$$

$$\frac{1500}{6.25} \times 0.8 = 192$$

Illuminance = **192 lx**

* * * * *

Reflection

One method of changing the direction of light is by the process of reflection, which may be of two types as shown in figure 5.10:

(1) *Specular reflection* is direct reflection in one direction only. The angle of incidence (i) equals the angle of reflection (r).
(2) *Diffuse reflection* is reflection in which the light is scattered in various directions.

Most practical surfaces give a mixture of free and diffuse reflection properties. The amount of reflection at a surface is measured by the *reflection factor* or reflectance.

REFLECTANCE is the ratio of the luminous flux reflected from a surface to the flux incident upon the surface.

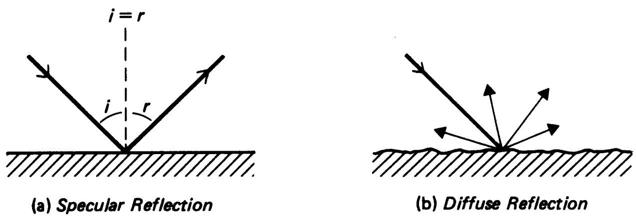


FIGURE 5.10 *Reflection of light*

TABLE 5.1 *Reflectances of surfaces*

Surface	Reflectance
White emulsion paint on plaster	0.8
White emulsion paint on concrete	0.6
Concrete: light grey	0.4
Timber: birch, beech, or similar	0.3
Bricks: red fletton	0.35
Quarry tiles: red	0.1

Reflectances have a maximum value of 1 and typical values are given in table 5.1.

Reflected components of light are an important factor in illumination. The following is a simple worked example and the influence of reflectances will be referred to again in the section on lighting design.

* * * * *

Worked example 5.4

A point source of light with a luminous intensity of 1800 cd is set 3 m above the floor and 1 m below the ceiling which has a reflectance of 0.5. Calculate the direct and reflected components of the illuminance on the floor beneath the light.

(a) $E = ?$, $I = 1800$ cd, $d = 3$ m

Using

$$E = \frac{I}{d^2}$$

$$= \frac{1800}{3^2} = 200$$

Direct component = **200 lx**

(b) $E = ?$, $I = 1800$ cd, $d = 1 + 1 + 3 = 5$ m

Using

$$E = \frac{I}{d^2} \times \text{reflectance}$$

$$= \frac{1800}{5^2} \times 0.5 = 36$$

Reflected component = **36 lx**

* * * * *

Luminance

The appearance of an object is affected by the amount of light it emits or reflects compared to the area of its surface. This idea of surface 'brightness' is termed luminance.

LUMINANCE (L) is a measure of the ability of an area of light source, or reflecting surface, to produce the sensation of brightness.

For example, a light bulb and a fluorescent tube may each have the same luminous intensity. But, because of its larger surface area, the fluorescent tube would have a lower luminance. There are two types of luminance measurement:

(1) *Self-luminous Sources* These include light sources and reflecting surfaces which can be considered as a source of light. The luminance is given by the formula:

$$L = \frac{\text{Luminous intensity in a given direction}}{\text{Area of source as seen from that direction}}$$

UNIT: candela per square metre (cd/m^2). This is the correct SI unit.

(2) *Reflecting Surfaces* For reflecting surfaces only, the luminance can be expressed in terms of the luminous flux emitted per unit area.

UNIT: apostilb (asb) where 1 asb = 1 lm/m^2.

The apostilb is an alternative unit of luminance which is convenient for some calculations. 1 apostilb = $1/\pi$ cd/m^2. This luminance of a surface can be calculated as the product of the illuminance and the reflectance of a surface.

Glare

The eye can detect a wide range of light levels but vision is affected by the range of brightness visible at any one time.

GLARE is the discomfort or impairment of vision caused by an excessive range of brightness in the visual field.

Glare can be caused by lamps, windows and painted surfaces appearing too bright in comparison with the general background. Glare can be further described as disability and discomfort glare.

Disability Glare Disability glare is the glare that lessens the ability to see detail. It does not necessarily cause visual discomfort. For example, excessive reflections from shiny white paper can cause disability glare while reading.

Discomfort Glare Discomfort glare is the glare that causes visual discomfort without necessarily lessening the ability to see detail. An unshielded light bulb is a common example of discomfort glare. The amount of discomfort depends on the angle of view and the type of location. If the direction of view is fixed on a particular visual task, then glare caused by lighting conditions will be more noticeable.

Light meters

A *photometer* is an instrument that measures the luminous intensity of a light source by comparing it with a standard source whose intensity is known. The distances between the instrument and the two light sources are adjusted until they each provide the same illuminance at the photometer. The human eye is the best judge of this equal illuminance and photometers generally use some system which allows two screens to be compared. The inverse square law can be used to calculate the unknown intensity. For equal illuminance:

$$\frac{I_1}{d_1^2} = \frac{I_2}{d_2^2}$$

where I_1 = intensity of source at distance d_1,
I_2 = intensity of source at distance d_2.

A *photocell* light meter is an instrument that directly measures the illuminance on a surface. The electrical resistance of some semiconductors, such as selenium, changes with exposure to light and this property is used in an electrical circuit connected to a galvanometer. This meter may be calibrated in lux.

Directional quality

The appearance of an object is affected by the direction of light as well as by the quantity of light illuminating the object.

The *illumination vector* specifies the quantity of light from a specified direction, such as horizontal illumination.

Scalar illuminance is the total illuminance caused by light from all directions, including reflected light.

Vector/scalar ratio is a measure of the directional strength of light at a particular point. A vector/scalar ratio of 3.0 indicates lighting with very strong directional qualities, such as that provided by spotlights or direct sunlight. The effect is of strong contrasts and dark shadows. A vector/scalar ratio of 0.5 indicates lighting with weak directional qualities, such as that provided by indirect lighting by reflections – this lighting is free of shadows and makes objects look 'flat'.

COLOUR

Colour is a subjective effect that occurs in the brain when the eye is stimulated by various wavelengths of light. It is difficult to specify colour by any method and especially difficult by means of this black and white printing. But the description and measurement of colour is important in the design of lighting schemes, as well as in photographic films, paints, dyes and inks.

Spectral energy distribution

The brain can experience the impression of only one colour at a time and it cannot detect how that colour has been made up. It is possible for different combinations of different wavelengths to produce the same colour impression in the brain.

A *spectrometer* is an instrument that disperses light into its component wavelengths and measures the amount of light energy radiated at each wavelength. This spectral energy distribution reveals if some light is being emitted at each wavelength (continuous spectrum), or only at certain wavelengths (discontinuous or line spectrum). Some spectral curves are shown in figure 5.11.

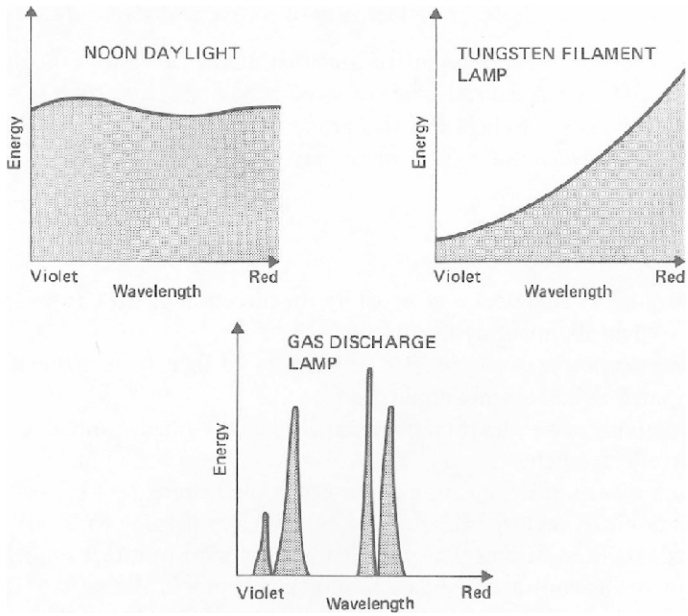


FIGURE 5.11 *Spectral energy distribution*

Colour systems

CIE Colour Co-ordinates The Commission Internationale de l'Eclairage (CIE) have produced many international lighting standards. The CIE co-ordinate system describes any colour as a mixture of three monochromatic primary colours. Three co-ordinates specify how much of each primary colour needs to be mixed to reproduce the colour being described.

Munsell System This is a system used by some architects and interior designers for classifying the colour of surfaces. It specifies colours in terms of three factors called hue (basic colour), chroma (intensity of colour), and value (greyness).

Colour reproduction

The human vision can distinguish many hundreds of different colours and intensities of colour. Modern systems of colour representation by ink, photography and television can reproduce these many colours to the satisfaction of the eye, yet such systems use just a few basic colours.

It has been shown that white light contains all the colours of the spectrum which can be recombined to give white light again. White light can also be split into just three colours which recombine to give white light. In addition to white light, *any* colour can be reproduced by various combinations of three suitable primary colours. Most colour systems use this trichromatic method of reproduction and the eye is believed to send its information to the brain by a similar method of coding.

Newton's discoveries concerning the combination of colours initially seemed to disagree with the experience of mixing paints. This confusion about combining colours still arises sometimes because they can be mixed by two different methods which have different effects: additive and subtractive mixing.

Additive colour

If coloured lights are *added* together then they will produce other colours and if the three primary additive colours are combined in equal proportions they will produce *white* light.

Additive Primary Colours

Red + Green + Blue = White

Red + Green = Yellow

Green + Blue = Cyan (a sky blue)

Red + Blue = Magenta (a purple-red)

Applications of Additive Colour Some of the important applications of additive colour mixing follow:

1. *Stage lighting* By using three or more coloured light sources, on dimming controls, any colour effect can be obtained.
2. *Colour television* The television screen has many small red, green, and blue prosphors, each type controlled by a separate beam of electrons. A close look

at a colour television will reveal that white doesn't actually exist on the screen but is an effect produced in the brain.

3. *Colour printing* Some processes, such as gravure, produce a mosaic of ink dots which effectively act as an additive system.

Subtractive colour

If colours are subtracted from white light then other colours will be produced and if the three primary subtractive colours are combined in equal proportions the result will be *darkness*.

Subtractive Primary Colours

Cyan	subtracts red	These pairs are termed *complimentary* colours
Magenta	subtracts green	
Yellow	subtracts blue	

White light can be considered as a combination of red, green, and blue light. Materials that transmit or reflect light absorb selected wavelengths and pass the remaining light to the eye. Combining two or more paints, or coloured layers, has a cumulative effect, as shown in figure 5.12.

A red surface is defined by the fact that it subtracts green and blue from white light, leaving only red light to reach the eye. A white surface reflects all colours. If the colour content of the light source changes then the appearance of the surface may change. This effect is important when comparing surface colours under different types of light source.

Applications of Subtractive Colour Most colour is seen as a result of subtractive processes and some common applications are given below:

1. *Paint pigments* Paint colours are mixed according to subtractive principles, even though, for simplicity, the primary colours are often called red, yellow, and blue instead of magenta, yellow, and cyan.
2. *Colour photographs* All colour transparencies and colour prints are finally composed of different densities of three basic dyes: cyan, magenta, and yellow.

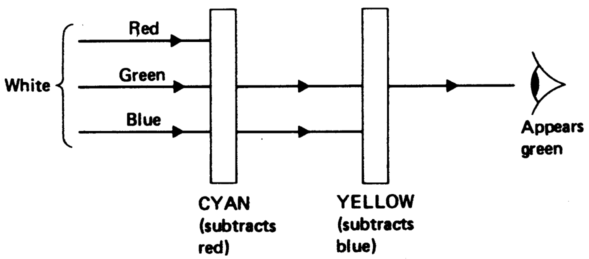


FIGURE 5.12 *Combination of subtractive colours*

3. *Colour printing* White paper is over-printed three times with the three basic colours of printing ink, cyan, magenta, and yellow. Black ink is also used to achieve extra density.

EXERCISES

1 A small lamp emits a total luminous flux of 1257 lm in all directions. Calculate the luminous intensity of this light source.

2 A point source of light has an intensity of 410 cd and radiates uniformly in all directions. Calculate:
(a) the quantity of flux flowing into a hemisphere; and
(b) the average illuminance produced on the inside surface of this hemisphere if it has a radius of 1.5 m.

3 A small lamp has a mean luminous intensity of 80 cd. Calculate the maximum direct illuminance the lamp produces on a surface:
(a) at 0.8 m; and
(b) at 3.2 m distance from the lamp.

4 A street lamp has a uniform intensity of 1200 cd. It is positioned 7 m above the centre line of a road which is 8 m wide. Calculate:
(a) the illuminance on the road surface directly below the lamp; and
(b) the illuminance at the edge of the roadway.

5 A uniform point source of light emits a total flux of 2500 lm. It is suspended 800 mm above the centre of a square table with sides of length 600 mm. Calculate the minimum and maximum illuminances produced on the table.

6 A photometer is positioned on a direct line between two lamps. When each side of the photometer receives equal illuminance the distances from the photometer are 500 mm to lamp A, and 650 mm to lamp B. Lamp A is known to have a luminous intensity of 70 cd. Calculate the luminous intensity of lamp B.

7 Use a diagram to predict and demonstrate the appearance of white light after it has passed through a cyan glass and then a magenta glass. Assume that white light is simply composed of red, green, and blue.

8 Use a diagram to predict and demonstrate the appearance of a blue surface which is illuminated by yellow light.

ANSWERS

1 100 cd
2 2576 lm, 182 lx
3 125 lx, 7.81 lx
4 24.5 lx, 18.5 lx
5 310.9 lx, 214.3 lx
6 118.3 cd

6 Artificial Lighting

The type of lighting chosen for a building is closely linked to other decisions made about the building, such as the basic plan shape, the type and extent of windows and the type of heating. The subject of this chapter is artificial lighting, and chapter 7, following, deals with natural lighting. Although the principles of these two topics are treated separately it is important that they are considered together when designing a building.

The main functions of artificial lighting can be summarised as follows:

1. to provide enough light for people to carry out a particular activity;
2. to provide enough light for people to move about with ease and safety;
3. to display the features of the building in a manner suitable for its character and purpose.

To achieve these aims it is necessary to consider the properties of lamps, of the lamp fittings and of the room surfaces that surround them.

LAMPS

The oldest source of artificial light is the flame from fires, candles and oil lamps where light is produced as one of the products of chemical combustion. Modern sources of artificial light convert electrical energy to light energy and are of two general types: incandescent sources and gas discharge sources.

Incandescent Lamps Incandescent sources produce light by heating substances to a temperature at which they glow and are luminous. Incandescence can be achieved by heating with a flame but in an electric lamp, such as the light bulb, a metal wire is heated by an electric current.

Discharge Lamps Discharge lamps produce light by passing an electric current through a gas or vapour that has become ionised and hence able to conduct electricity. At low gas pressures a luminous arc or discharge is formed between the electrodes and useful quantities of light are given off. Discharge lamps need special control gear in their circuits and the colour quality of their light is often poor.

The characteristics of the electric lamps used in modern lighting are summarised in table 6.1. Further details of these lamps and their properties are given in the following sections.

Properties of lamps

Luminous Efficacy The ability of a lamp to convert electrical energy to light energy is measured by its efficacy which is given by the following formula

$$\text{Luminous efficacy} = \frac{\text{Luminous flux output}}{\text{Electrical power input}}$$

UNIT: lumens/watt (lm/W).

The electrical running costs of a lamp can be calculated from its efficacy. The luminous efficacy of a lamp varies with its type and its wattage; exact data should be obtained from the manufacturer.

Life The luminous efficacy of a lamp decreases with time and for a discharge lamp it may fall by as much as 50 per cent before the lamp fails. The nominal life of a lamp is usually determined by the manufacturer by considering the failure rate of a particular model of lamp combined with its fall in light output. In a large installation it is economically desirable that all the lamps should be replaced at the same time on a specified maintenance schedule.

Colour Temperature The qualities of light emitted by heated objects depend upon the temperature of the radiating object and this fact can be used to describe the colour of light. A theoretically perfect radiator, called a 'black body', is used as the standard for comparison.

The CORRELATED COLOUR TEMPERATURE (CCT) of a light source is the absolute temperature of a perfect radiator when the colour appearance of the radiator best matches that of the light source.

UNIT: kelvin (K).

This method of specifying colour quality is most suitable for light sources that emit a continuous spectrum, such as those giving various types of 'white' light. The lower values of colour temperature indicate light with a higher red content. Some examples of colour temperatures are given below:

Clear sky	12 000–24 000 K
Overcast sky	5000–8000 K
Tubular fluorescent lamps	3000–6500 K
Tungsten filament lamps	2700–3100 K

TABLE 6.1 *Characteristics of electric lamps**

Lamp type (code)	Wattage range	Typical efficacy (lm/W)	Nominal life (hours)	Colour temperature (K)	Typical applications
Tungsten filament (GLS)	40–200	12	1000	2700	Homes, hotels and restaurants
Tungsten halogen (T–H)	300–2000	21	2000	2900	Area and display lighting
Tubular fluorescent (MCF)	20–125	60	8000 +	3000–6500	Offices and shops
Mercury fluorescent (MCB)	50–2000	60	8000 +	4000	Factories and roadways
Mercury halide (MBI)	250–3500	70	8000 +	4200	Factories and shops
Low-pressure sodium (SOX)	35–180	180 (at 180 W)	8000 +	n.a.	Roadways and area lighting
High-pressure sodium (SON)	70–1000	125 (at 400 W)	8000 +	2100	Factories and roadways

* Values for the efficacy and life of most discharge lamps are subject to improvements – See manufacturers' data.

Colour Rendering The colour appearance of a surface is affected by the quality of light from the source. Colour rendering is the ability of a light source to reveal the colour appearance of surfaces. This ability is measured by comparing the appearance of objects under the light source with their appearance under a reference source such as daylight.

One system specifies the colour rendering of lamps by a *colour rendering index* (R_a) which has a value of 100 for an ideal lamp. Practical sources of white light range in R_a value between 50 and 90.

Tungsten filament lamps

The general lighting service (GLS) lamp, or common light bulb, is an incandescent type of lamp. An electric current passes through a coil of tungsten wire and heats it to incandescence at about 2800 K. To prevent oxidation and evaporation of the metal filament it is placed inside a glass envelope and surrounded by an inert atmosphere of unreactive gases such as nitrogen and argon. The construction of a typical lamp is shown in figure 6.1.

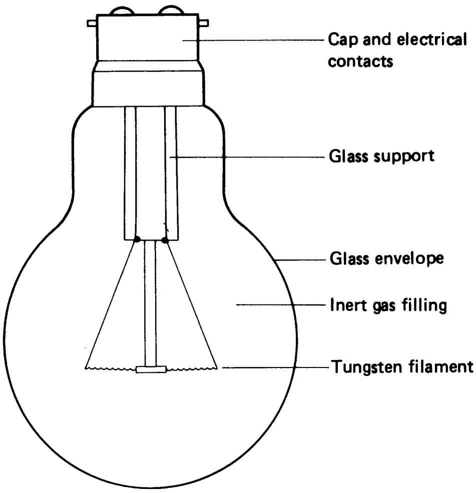


FIGURE 6.1 *Tungsten filament lamp*

The filament lamp produces a spectral distribution of light which is continuous but deficient in blue, as shown previously in figure 5.11. This quality of light is seen as 'warm' and is considered generally suitable for social and domestic applications.

The cost of a tungsten filament lamp is low and its installation is simple, but the relatively short life of the lamp can cause the labour costs of replacement to be high. The low luminous efficacy of the lamp produces high electrical running costs and about 90 per cent of the energy consumed is given off as heat, most of it radiant heat.

Tungsten–halogen lamps have filaments that are able to be run at higher temperatures because of the presence of a halogen gas, such as bromine or iodine, which helps to slow evaporation of the tungsten from the filament. The result is an increase in luminous efficiency and life which is particularly useful for applications such as floodlights and car headlamps.

Fluorescent lamps

The common tubular fluorescent (MCF) lamp is a form of gas discharge lamp. An electric discharge is established between the electrodes inside a glass tube containing mercury vapour at low pressure. The energised mercury atoms emit ultra-violet (u.v.) radiation and some blue–green light. The coating of fluorescent powders on the inside of the glass tube absorbs the u.v. energy and re-radiates it as light in the visible part of the spectrum.

Figure 6.2 illustrates the construction of a typical lamp and an example of the special electrical control gear that it requires. This gear is needed to provide a starting pulse of high voltage, to control the discharge current, and to improve the electrical power factor.

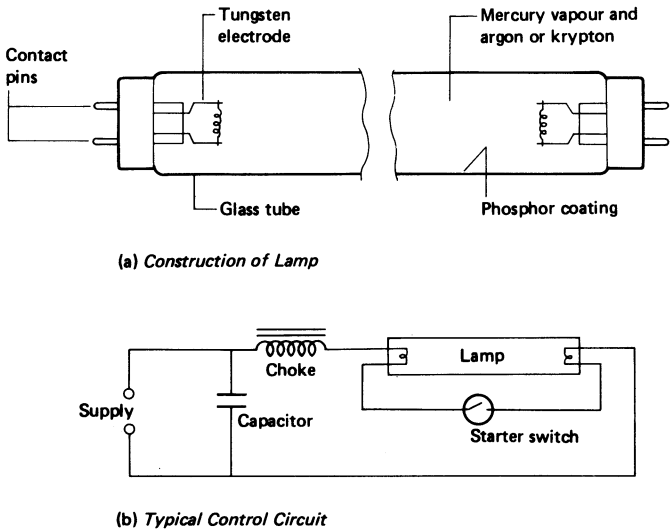


FIGURE 6.2 *Tubular fluorescent lamp*

The colour quality of the light from a fluorescent lamp can be varied by using suitable mixtures of the metallic phosphors, which make up the fluorescent coating. Lamps are available with colour temperatures ranging from 3000 K ('warm') to 6500 K ('daylight'). The large surface area of this type of lamp produces lighting of a relatively non-directional 'flat' quality and with low glare characteristics. It is possible for the cyclic nature of the gas discharge to cause a stroboscopic effect – an apparent change of motion, when viewing moving objects such as machinery. Modern electronic control gear or new lamps with shielded electrodes and high-efficiency phosphors avoid stroboscopic effects.

The luminous efficacy of the tubular fluorescent lamp is several times better than that of the tungsten filament lamp, and improvements are continuing. The efficacy of the lamp decreases with the age of the lamp and is affected by the surrounding temperature. The initial cost of a fluorescent lamp is higher than that of the tungsten filament lamp but this is soon offset by the lower running costs arising from their long life and high efficacy. Fluorescent lamps are being developed in compact form with the control gear incorporated inside the lamp and with a light quality suitable for domestic use. The use of such lamps reduces electrical energy consumption and gives lower overall lighting costs.

Discharge lamps

Apart from the well-known tubular fluorescent lamp, gas discharge lamps have in the past been restricted to outdoor lighting, such as for roadways, where their generally poor colour qualities have not been important. Some modern types of discharge lamp have a colour rendering that is good enough for large-scale lighting inside buildings such as factories and warehouses. The high efficacy and long life of such lamps outweigh the initial installation costs.

Mercury Discharge Lamps An uncorrected mercury lamp emits sharp spectral peaks of light at certain blue and green wavelengths. A better spectral distribution is obtained by coating the glass envelope with fluorescent powders (MBF lamps).

In the mercury halide (MBI) lamp metallic halides are added to the basic gas discharge in order to produce better colour rendering and to raise the efficacy.

Sodium Discharge Lamps Low-pressure sodium (SOX) lamps produce a distinctive yellow light that is virtually monochromatic and gives poor colour rendering.

High-pressure sodium (SON) lamps produce a continuous spectrum without much blue light but with a colour rendering that is acceptable for some situations.

LUMINAIRES

A luminaire is the light fitting that holds or contains a lamp. Luminaires usually absorb and redirect some of the luminous flux emitted by the lamp and, in the design of lighting installations, the choice of lamp must be combined with the choice of luminaire. The specification of luminaires is therefore important and this section outlines the methods used to classify luminaires according to the effect that they have on light distribution.

Luminaires may also serve a number of mechanical and electrical purposes such as positioning the lamp in space, protecting the lamp, and containing the control gear. Physical properties that may be relevant in the choice of the luminaire include its electrical insulation, moisture resistance, appearance and durability.

Polar curves

Polar curves show the directional qualities of light from a lamp or luminaire by a graphical plot onto polar co-ordinate paper, as shown in figure 6.3. The luminous

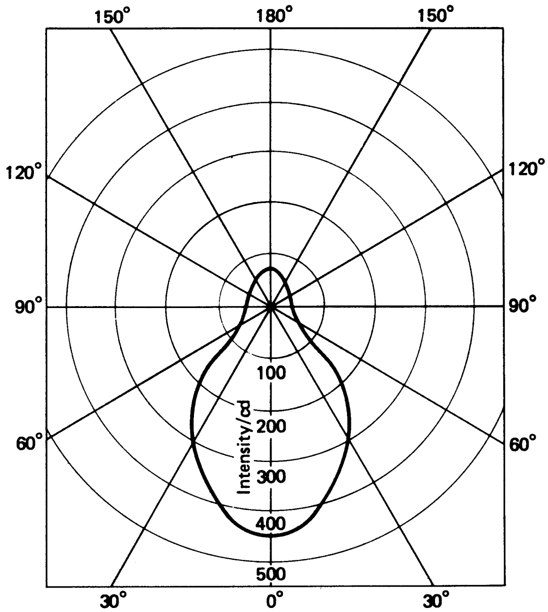


FIGURE 6.3 *Polar curve of a luminaire*

intensity of a lamp in any direction can be measured by means of a photometer, the results plotted and joined by a curve which then represents the distribution of light output from the fitting. If the distribution is not symmetrical about the vertical axis, as in a linear fitting, then more than one vertical plane needs to be plotted.

Light output ratio

It is convenient to try and describe the distribution of light from a luminaire by a system of numbers. One system is to classify luminaires by the proportion of the total light from the luminaire emitted into the upper and lower hemispheres formed by a plane through the middle of the lamp filament. These classifications are as follows:

Light output Ratio

$$\text{LOR} = \frac{\text{Total light output of luminaire}}{\text{Light output of its lamp(s)}}$$

Downward light output Ratio

$$\text{DLOR} = \frac{\text{Light output of luminaire downwards}}{\text{Light output of its lamp(s)}}$$

Upward light output Ratio

$$\text{ULOR} = \frac{\text{Light output of luminaire upwards}}{\text{Light output of its lamp(s)}}$$

So that

$$\text{LOR} = \text{DLOR} + \text{ULOR}$$

Luminaires can be broadly divided into five types according to the proportion of light emitted upwards or downwards. Figure 6.4 indicates these divisions using luminaires with generalised shapes.

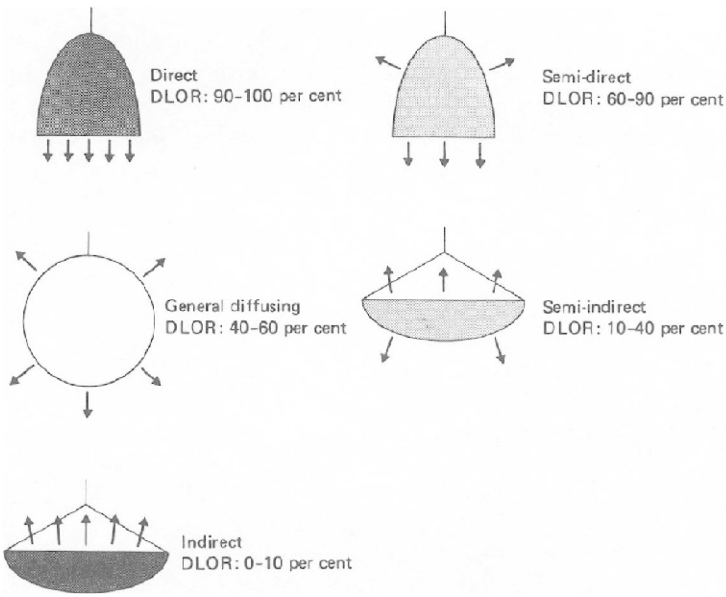


FIGURE 6.4 *General types of luminaire*

British zonal system

The British Zonal or BZ System classifies luminaires into 10 standard light distributions with BZ numbers from 1 to 10. BZ1 indicates a distribution of light that is mainly downwards and BZ10 a distribution that is mainly upwards. The BZ number is obtained from a combination of the properties of the luminaire and the room surfaces, which are measured by the following terms.

1. **Direct ratio** is the proportion of the total downward flux from the luminaires which falls directly on the working plane.

2. **Room index** is a number which takes account of the proportions of the room by the following formula

$$RI = \frac{L \times W}{H_m(L + W)}$$

where

L = length of the room

W = width of the room

H_m = mounted height of the luminaire above the working plane

A plot of direct ratio against room index for a particular luminaire gives a curve which can be described by the BZ number of the standard curve to which it is the closest fit. Figure 6.5 illustrates the standard curves of some BZ numbers. The actual curves of most luminaires cross from one BZ zone to another as the room index varies.

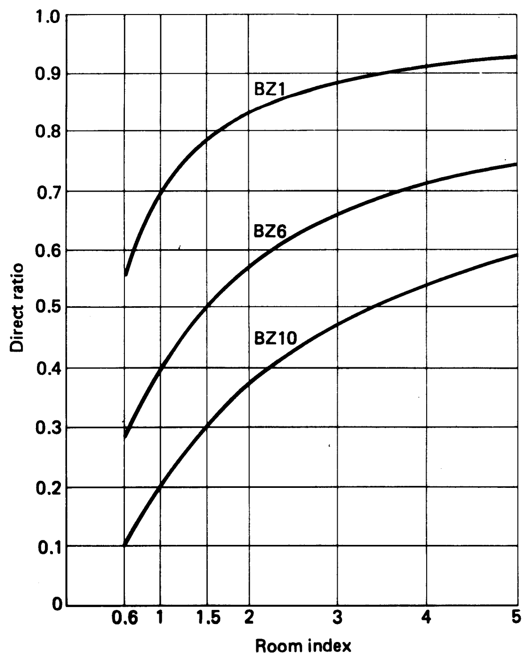


FIGURE 6.5 *BZ curves for luminaires*

LIGHTING DESIGN

Illuminance levels

The quantity of light reaching a certain surface is usually the main consideration in designing a lighting system. This quantity of light on a surface is specified by illuminance measured in lux and, as this level varies across the working plane, an average figure is used.

Service illuminance is the mean illuminance averaged over the area being considered and throughout the maintenance cycle of the lighting system.

The illuminance needed for a particular task depends upon the visual difficulty of the task, the average standard of eyesight involved and the type of performance expected. It can be shown that the speed and accuracy of various types of work are affected by the level of illuminance supplied. Table 6.2 gives some of the standard service illuminance levels that are recommended for a variety of interiors and tasks. The values represent current good practice, which takes into account the visual needs, the practical experience, and the efficient use of energy relating to the situation.

Lumen method

Chapter 5 explained how illuminance is affected by the distance and the angles between the illuminated surface and the light source, and by the reflectances of the surrounding surfaces. In an interior where there is more than one light source and there are several reflecting surfaces, the repeated combination of these effects makes calculation difficult if basic formulas are used. Some simplified methods have been developed and are found to give satisfactory results.

The lumen method is a commonly used technique of lighting design which is valid if the luminaires are to be mounted overhead in a regular pattern. The luminous flux output ('lumens') of each lamp needs to be known, as do details of the luminaires and the room surfaces. Usually the illuminance is already specified, the designer chooses suitable lamps and luminaires, and then wishes to know how many lamps are required to meet the specification. The number of lamps is given by the formula

$$N = \frac{E \times A}{F \times UF \times MF}$$

(*text cont. on page 123*)

TABLE 6.2 *Standard service illuminances*

Location	Illuminance (lux)	Position
General areas		
Entrance halls	150	1.2 m
Stairs	150	treads
Passageways	100	1.2 m
Outdoor entrances	30	ground
General assembly		
Casual work	200	wp
Rough work (e.g. heavy machinery)	300	wp
Medium work (e.g. vehicle bodies)	500	wp
Fine work (e.g. electronic assembly)	1000	bench
Very fine work (e.g. instrument assembly)	1500	bench
Offices		
General clerical	500	desk
Typing room	750	copy
Drawing offices	750	boards
Filing rooms	300	labels
Shops		
Counters	500	horizontal
Supermarkets	500	vertical
Education		
Chalkboard	500	vertical
Classrooms	300	desk
Laboratories	500	bench
Hotels		
Bars	150	table
Restaurants	100	table
Kitchens	500	wp
Homes		
General living room	50	wp
Casual reading	150	task
Studies	300	task
Kitchen	300	wp
General bedroom	50	floor
Halls and landings	150	floor
Recreation		
Gymnasium	500	floor
Squash rackets	300	floor
Swimming pool	300	water
Table tennis	300	table

Values from *CIBS Code of Interior Lighting*
wp: working plane

where

N = number of lamps required

E = illuminance level required (lux)

A = area at working plane height (m^2)

F = average luminous flux from each lamp (lm)

UF = utilisation factor, an allowance for the light distribution of the luminaire and the room surfaces

MF = maintenance factor, an allowance for reduced light output because of deterioration and dirt

The *utilisation factor* is the ratio of the total flux (including reflected light) received by a surface to the total flux output of the lamps. The utilisation factor can be calculated directly or, more usually, obtained from tables which combine the distribution properties of the luminaire with the room index and with the reflectances of the room surface. Table 6.3 lists the utilisation factors for some representative types of luminaire.

The *maintenance factor* is the ratio of the illuminance provided by a lighting system when it is in the average state of dirtiness expected, to the illuminance from the same system when it is clean. The value of the maintenance factor depends upon the use of the room and the intervals between cleaning. Tables of recommended maintenance factors are available; a factor of 0.8 is usual for normal interiors.

The number of lamps calculated from the lumen formula usually needs to be rounded up to a convenient figure and the layout of the luminaires decided upon. In order that the illuminance provided does not fall below a minimum value the fittings must be placed in a regular grid pattern and their spacing must not exceed certain distances. This maximum spacing depends on the type of luminaire and the height at which they are set. Typical values are as follows

For fluorescent tubes in diffusing luminaires $S_{max} = 1.5 \times H_m$

and

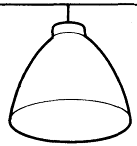
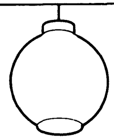
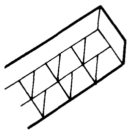
for filament lamps in direct luminaires $S_{max} = 1.0 \times H_m$

where

S_{max} = maximum horizontal spacing between fittings;

H_m = mounted height of fitting above the working plane, as shown in figure 6.6. Take working plane as 0.85 m above floor level unless otherwise specified.

TABLE 6.3 *Utilisation factors for some luminaires*

Description of fitting	Typical outline LOR	Basic downward LOR %	Ceiling	Reflectances 0.7			0.5			0.3		
			Walls	0.5	0.3	0.1	0.5	0.3	0.1	0.5	0.3	0.1
			Room index									
Aluminium industrial reflector, Aluminium or enamel high-bay reflector		70	0.6	0.39	0.36	0.33	0.39	0.36	0.33	0.39	0.35	0.33
			0.8	0.48	0.43	0.40	0.46	0.43	0.40	0.46	0.43	0.40
			1.0	0.52	0.49	0.45	0.52	0.48	0.45	0.52	0.48	0.45
			1.25	0.56	0.53	0.50	0.56	0.53	0.49	0.56	0.52	0.42
			1.5	0.60	0.57	0.54	0.59	0.57	0.53	0.59	0.55	0.53
			2.0	0.65	0.62	0.59	0.63	0.60	0.58	0.63	0.59	0.57
			2.5	0.67	0.64	0.62	0.65	0.62	0.61	0.65	0.62	0.60
			3.0	0.69	0.66	0.64	0.67	0.64	0.63	0.67	0.64	0.62
			4.0	0.71	0.68	0.67	0.69	0.67	0.65	0.69	0.66	0.64
			5.0	0.72	0.70	0.69	0.71	0.69	0.67	0.71	0.67	0.66
Near-spherical diffuser, open beneath		50	0.6	0.28	0.22	0.18	0.25	0.20	0.17	0.22	0.18	0.16
			0.8	0.39	0.30	0.26	0.33	0.28	0.23	0.27	0.25	0.22
			1.0	0.43	0.36	0.32	0.38	0.34	0.29	0.31	0.29	0.26
			1.25	0.48	0.41	0.37	0.42	0.38	0.33	0.34	0.32	0.29
			1.5	0.52	0.46	0.41	0.46	0.41	0.37	0.37	0.35	0.32
			2.0	0.58	0.52	0.47	0.50	0.48	0.43	0.42	0.39	0.36
			2.5	0.62	0.56	0.52	0.54	0.50	0.47	0.45	0.42	0.40
			3.0	0.65	0.60	0.56	0.57	0.53	0.50	0.48	0.45	0.43
			4.0	0.68	0.64	0.61	0.60	0.56	0.54	0.51	0.48	0.46
			5.0	0.71	0.60	0.65	0.62	0.59	0.57	0.53	0.50	0.48
Recessed louvre trough with optically designed reflecting surfaces		50	0.6	0.28	0.25	0.23	0.28	0.25	0.23	0.28	0.25	0.23
			0.8	0.34	0.31	0.28	0.33	0.30	0.28	0.33	0.30	0.28
			1.0	0.37	0.36	0.32	0.37	0.34	0.32	0.37	0.34	0.32
			1.25	0.40	0.38	0.35	0.40	0.37	0.35	0.40	0.37	0.35
			1.5	0.43	0.41	0.38	0.42	0.40	0.38	0.42	0.39	0.38
			2.0	0.46	0.44	0.42	0.45	0.43	0.41	0.44	0.42	0.41
			2.5	0.48	0.46	0.44	0.47	0.45	0.43	0.46	0.44	0.43
			3.0	0.49	0.47	0.46	0.48	0.46	0.45	0.47	0.45	0.44
			4.0	0.50	0.49	0.48	0.49	0.48	0.47	0.48	0.47	0.46
			5.0	0.51	0.50	0.49	0.50	0.49	0.48	0.49	0.48	0.47

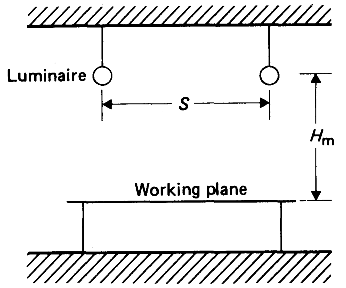


FIGURE 6.6 *Spacing of luminaires*

*   *   *   *   *

Worked example 6.1

A factory space measuring 40 m by 12 m by 5 m in height requires a service illuminance of 500 lux on the work benches which are set 1 m above the floor. The 65 W tubular fluorescent lamps chosen have a luminous efficacy of 80 lm/W. They are to be mounted on the ceiling in luminaires which have a DLOR of 50 per cent. The room reflectances are 0.5 for the ceiling and 0.3 for the walls; 0.7 is the assumed maintenance factor. Use the lumen method of design to calculate the number of lamps required and suggest a suitable layout.

$E = 500$ lx, $F = 65 \times 80 = 5200$ lm

$L = 40$ m, $W = 12$ m, $H_m = 4 - 1 = 3$ m

$A = 40 \times 12 = 480$ m $MF = 0.7$

$$RI = \frac{L \times W}{\bar{H}_m(L + W)} = \frac{40 \times 12}{3(40 + 12)} = 3.0$$

Reflectances: ceiling 0.5, walls 0.3

$UF = 0.46$ (from table 6.3 using above data)

Using

$$n = \frac{E \times A}{F \times UF \times MF}$$

$$= \frac{500 \times 480}{5200 \times 0.46 \times 0.7} = 143.3$$

Number of lamps required = **144**

Suggest 9 rows of 16 luminaires

Check spacing: $S_{max} = 1.5 \times H_m = 1.5 \times 3 = 4.5$ m.

*   *   *   *   *

Glare index

Glare was defined in the previous chapter as the discomfort or impairment of vision caused by an excessive range of brightness in the visual field. The usual causes of glare in buildings are bright skies seen through windows and direct views of bright lamps. The glare is most likely to be discomfort glare which, over a period of time, can cause annoyance and affect efficiency.

GLARE INDEX is a numerical measure of discomfort glare which enables glare to be assessed and acceptable limits recommended.

The glare index is calculated from the following: a knowledge of the positions of the source and the viewpoint; the luminances of the source and the surroundings; and the size of the source. The calculated index may be compared with the maximum index recommended for the particular environment.

Glare indices for artificial lighting usually range from 10 for a low-brightness fitting, to 30 for an unshielded lamp. A typical glare index is 19, which is the recommended limit for offices.

Lighting criteria

Many factors may be relevant to the design of a particular lighting system. The following list summarises the main factors that usually need to be considered; the priorities will depend upon the type of situation:

1. *Light quantity* Depends upon the nature of the task and the light output of lamp and luminaire. Usually specified by illuminance level in lux.
2. *Natural light* May be used as a complete source of light or to supplement artificial light sources. Daylighting is the topic of the next chapter.
3. *Colour quality* Depends upon the requirements of the task and the colour rendering properties of the source. It can be specified by spectral distribution, colour temperature and the colour rendering index.
4. *Glare* Depends upon the brightness and contrast of light sources and surfaces, and the viewing angles. It is usually specified by a glare index.
5. *Directional quality* Depends upon three-dimensional effect required and the nature of the lamp and luminaire. It can be specified by vector and scalar illuminance.
6. *Energy use* Depends upon the electrical efficiency of the lamps and the use of switches. All lamps give off heat, which can be a significant source of heat gain in a building. Windows providing natural light can be a significant source of heat loss and solar gain.
7. *Costs* Depend upon the initial cost of the fittings, the replacement cost of the lamps and the electricity consumption of the lamps.
8. *Physical properties* Include size, appearance and durability of fittings.

EXERCISES

1 A certain space needs to be illuminated with a total luminous flux of 18 000 lm. The tungsten filament lamps used are rated at 60 W each and have a luminous efficacy of 12 lm/W. Calculate:
(a) how many such lamps are required; and
(b) how many kilowatt hours of electrical energy are used by the lamps in a 12 hour period. (1 kWh = 1 kW x 1 hour).

2 Compare the costs of providing the above illumination 12 hours a day for 2 years with:
(a) tubular fluorescent lamps; and
(b) with tungsten filament lamps.
Use manufacturers' data or your own estimates for costs of lamps, fittings, and electrical energy. Table 6.1 may also be useful.

3 An area measuring 18 m by 8 m is to have a service illuminance of 300 lx. The tubular fluorescent lamps each have a luminous flux output of 2820 lm and the luminaires give a utilisation factor of 0.4. The maintenance factor assumed is 0.8. Calculate the number of lamps required and suggest a layout for them.

4 A classroom with an area 10 m by 6 m is illuminated by 18 tubular fluorescent lamps, each lamp 60 W with a luminous efficacy of 80 lm/W. The utilisation factor is 0.46 and the maintenance factor is 0.8. Calculate the average illuminance in the classroom.

5 A workshop is 12 m by 6 m by 4 m high and has workbenches 1 m high. Discharge lamps, each with an output of 3700 lm, are to be fitted in aluminium industrial reflectors at ceiling level. The surfaces have reflectances of 0.7 for the ceiling and 0.5 for the walls. The maintenance factor is 0.7. The illuminance required on the workbenches is 400 lx.
(a) Find the utilisation factor for the room (use table 6.3).
(b) Calculate the number of lamps required.

ANSWERS

1 25 lamps, 18 kWh
3 48 lamps
4 530 lx
5 0.56, 20 lamps

7 Natural Lighting

It is often necessary to provide a room with natural light from the Sun or the sky. The qualities of this natural light may be thought desirable for a pleasant environment or they may be needed to perform certain tasks, such as exacting work with colour. The natural light can be used as the sole source of interior lighting or can be combined with artificial light.

Daylight is usually admitted into a building by means of windows or skylights; but windows also transmit heat, sound and perhaps air. So the design of windows for a building – called *fenestration* – affects almost all the environmental variables. The provision of natural lighting in a building must not be designed without also considering questions of artificial lighting, heating, ventilation and sound control.

The quantity of natural light inside a room is governed by the factors listed below. By analysing these factors it is possible to describe daylight numerically and to predict its effects in a room:

1. the nature and brightness of the sky;
2. the size, shape and position of the windows;
3. reflections from surfaces inside the room;
4. reflections and obstructions from objects outside the room.

NATURAL LIGHT SOURCES

All natural daylight comes from the Sun, by way of the sky. But, while the Sun can be considered as a reasonably constant source of light, the light from the sky varies with the time of the day, with the season of the year and with the local weather.

In parts of the world with predominantly dry, sunny weather much of the natural light inside buildings is direct sunlight which has been reflected. In the United Kingdom, and similar countries where sunshine is unreliable, the overcast sky is considered as the main source of natural light. Because the sky continually varies it is necessary to define certain 'standard skies', with constant properties, for use in design work.

Direct sunlight

The levels of illuminance on the ground provided by light direct from the Sun may be as high as 100 000 lx in the summer. Direct sunlight should generally be avoided inside working buildings because it can easily cause unacceptable glare. Sun control devices were discussed in chapter 3. However, in domestic buildings a certain amount of Sun penetration is considered desirable by most people who live in temperate climate zones, such as North-West Europe. One guideline for Britain is that sides of all residential buildings which face east, south and west, should have at least one hour of sunshine on 1 March.

The prediction of changing patterns of sunlight and shadow on buildings is essentially one of geometry. The position of the Sun in the sky at different times needs to be known and this information is available, one form of presentation being sunpath diagrams such as those shown in figure 7.1. The dimensions and orientation of the building can then be combined, in drawings, with the solar information. Another approach is to use a model of the building and a movable light source which can imitate the movements of the Sun known as a *heliodon*.

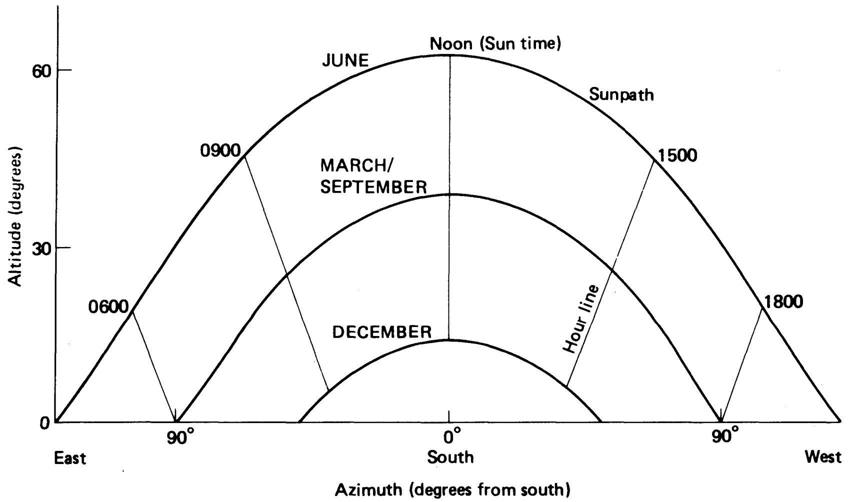


FIGURE 7.1 *Sunpaths for Southern England*

Uniform standard sky

The uniform sky is a standard overcast sky which is taken to have the same luminance in every direction of view. Viewed from an unobstructed point on the ground the sky effectively makes a hemispherical surface around that point. This surface emits light and the uniform sky assumes that every part of the surface is equally bright.

The illuminance at a point on the ground provided by an unobstructed overcast sky continually varies but a constant 5000 lx is taken as one standard for daylight calculations in Britain. This represents the light from a heavily overcast sky and is a conservative design assumption – the 5000 lx is actually exceeded for 85 per cent of normal working hours throughout the year.

Although the overcast sky of countries like Britain is not strictly uniform in luminance the model is useful for some purposes. A sky of uniform luminance is also a reasonable description of the *clear* skies in sunny climates.

CIE standard sky

The CIE sky is a standard overcast sky in which the luminance steadily increases above the horizon. This sky was defined by the Commission Internationale de l'Eclairage as being described by the formula

$$L_\theta = L_z \tfrac{1}{3} (1 + 2 \sin \theta)$$

where

L_θ = luminance of the sky at an altitude θ degrees above the horizon

L_z = luminance of the sky at the zenith.

Figure 7.2 illustrates the measurements referred to. The luminance of the CIE sky at the zenith is *three* times brighter than at the horizon. The CIE is found to be a good representation of conditions in many parts of the world, especially in regions like North-West Europe.

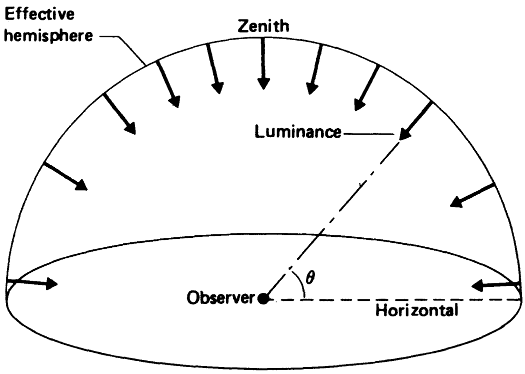


FIGURE 7.2 *Sky hemisphere*

DAYLIGHT FACTORS

The natural light that provides illumination inside a room is usually only a small fraction of the total light available from a complete sky. The level of illuminance provided varies as the brightness of the sky varies so it is not possible to specify daylight by a fixed illuminance level. The amount of daylight inside a room can be measured by comparing it with the total daylight available outside the room. This ratio, or daylight factor, is constant for a particular situation because the two parts of the ratio vary in the same manner as the sky changes.

DAYLIGHT FACTOR is the ratio between the actual illuminance at a point inside a room and the illuminance possible from an unobstructed hemisphere of the same sky.

Direct sunlight is excluded from both values of illuminance, and the daylight factor can be expressed by the following formula

$$DF = \frac{E_i}{E_o} \times 100$$

where

DF = daylight factor at a chosen reference point in the room (per cent)

E_i = illuminance at the reference point (lx)

E_o = illuminance at that point *if* the sky was unobstructed (lx)

The definition is a theoretical one as it is not actually possible to measure both types of illuminance at the same place. For purposes of specification and design a standard sky is assumed to give a minimum level of illuminance on the ground – often 5000 lx.

* * * * *

Worked example 7.1

A minimum daylight factor of 4 per cent is required at a certain point inside a room. Calculate the natural illuminance that this represents, assuming that an unobstructed standard sky gives an illuminance of 5000 lx.

DF = 4 per cent, E_i = ?, E_o = 5000 lx.

Using

$$DF = \frac{E_i}{E_o} \times 100$$

$$4 = \frac{E_i}{5000} \times 100$$

$$E_i = \frac{4 \times 5000}{100} = 200$$

Illuminance = **200 lx**

* * * * *

Recommended daylight factors

Daylight factors can be used to specify recommended levels of daylight for various interiors and tasks. Table 7.1 lists a selection of recommendations for interiors where daylight from side windows is a major source of light. Daylight factors vary for different points within a room so it is usual to quote average values or minimum values.

TABLE 7.1 *Recommended daylight levels*

Location	Average daylight factor (%)	Minimum daylight factor (%)	Surface
General office	5	2	desks
Classroom	5	2	desks
Entrance hall	2	0.6	working plane
Library	5	1.5	tables
Drawing office	5	2.5	boards
Sports hall	5	3.5	working plane

Source: CIBS Code of Interior Lighting.

Daylight factor components

The daylight reaching a particular point inside a room is made up of three principal components. The three components arrive at the same point by different types of path, as indicated in figure 7.3:

1. The **sky component** (SC) is the light received directly from the sky.

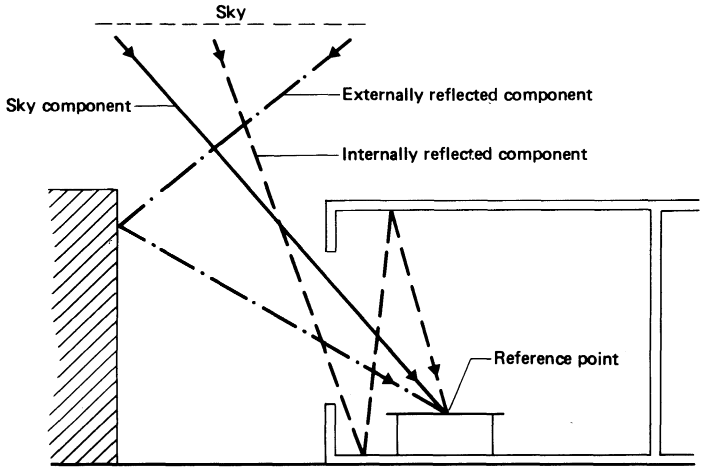


FIGURE 7.3 *Components of daylight factor*

2. The **externally reflected component** (ERC) is the light received directly by reflection from buildings and landscape outside the room.
3. The **internally reflected component** (IRC) is the light received from surfaces inside the room.

The three components can be analysed and calculated separately. The final daylight factor is the sum of the three separate components, so that:

Daylight factor = Sky component + Externally reflected component
+ Internally reflected component

DF = SC + ERC + IRC

Daylight factor contours

Daylight factor contours represent the distribution of daylight inside a room by means of lines which join points of equal daylight factor. The contours are commonly shown on a plan of the room at working plane height, as shown in figure 7.4. Contours around windows have characteristic lobe shapes which converge at the edge of the windows. Tall windows provide greater penetration of contours and multiple windows cause contours to join.

Assessment of daylight factor

When a building already exists the actual daylight distribution side of the building can be measured. A *daylight factor meter* is a specially calibrated light

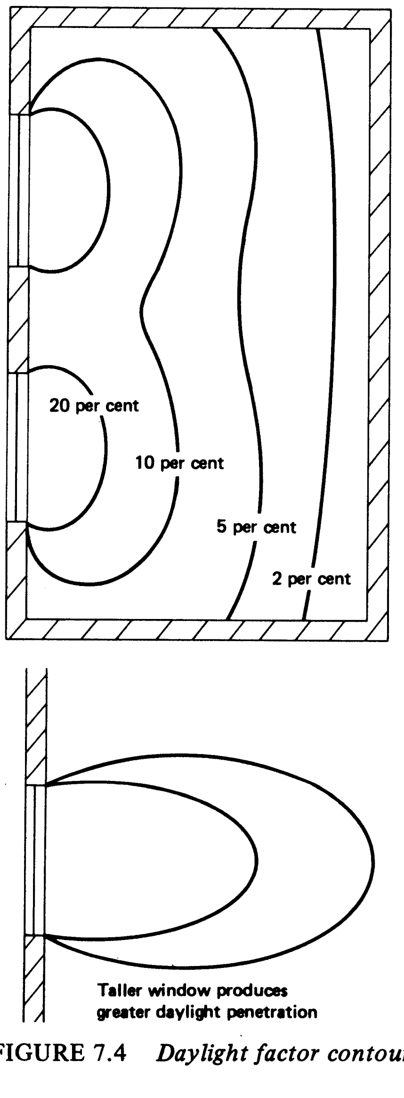


FIGURE 7.4 *Daylight factor contours*

meter which can give direct readings of the daylight factor at a particular point. A scale model of a room may also be used to measure daylight levels. The more usual procedure however, is to calculate the daylight factors *before* a room is built.

It is possible to calculate the three components of the daylight factor by using information about the size of the windows and room, the size of any external obstructions, and the reflectances of the room surfaces. The sky component is the major contributor to a daylight factor and can be considered as the percentage of an unobstructed sky that is visible from the reference point.

Methods for calculating the sky component include the use of tables of values, grids of the sky, and daylight factor protractors.

The *Waldram diagram* is a specially scaled grid representing half the hemisphere of sky. Using scaled plans of the room the area of sky visible through the window from the reference point is plotted onto the grid. The area of grid covered by this plot is proportional to the sky component at the reference point.

Building Research Establishment daylight factor protractors

The special protractors developed by the Building Research Establishment are widely used to determine daylight factors at the design stage of a building. Protractors are available for glazing set at different angles and for either a uniform sky or a CIE sky.

A protractor (as shown in figure 7.5) contains two semi-circular scales on transparent overlays, which are used with scale drawings of the room being assessed. The primary scale measures the initial sky component and an auxiliary scale makes a correction for the width of the windows. The protractor also contains an ordinary scale of angle used to find the angle of elevation of the patch of sky being assessed.

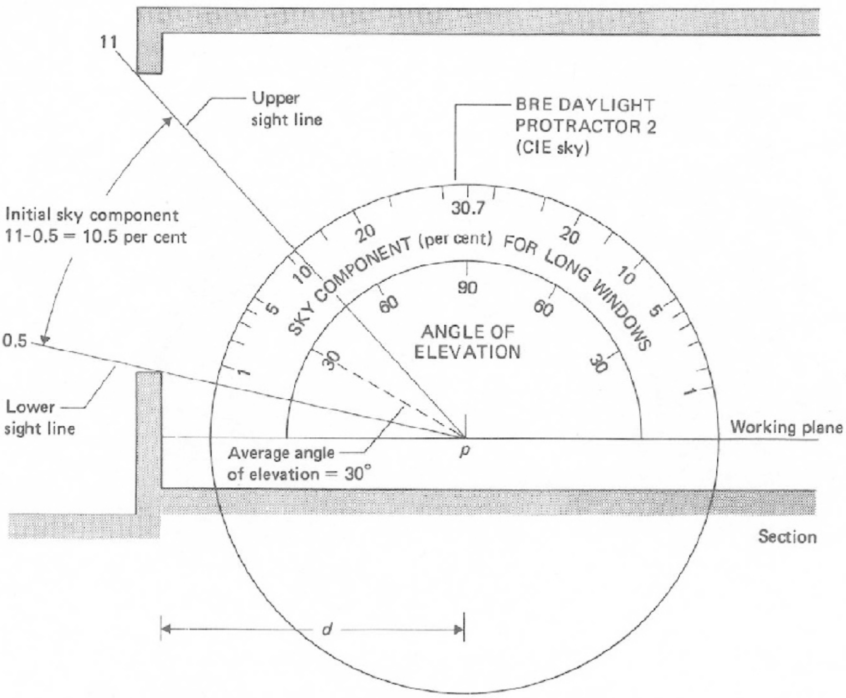


FIGURE 7.5 *BRE Daylight Protractor on section drawing*

Calculation of Sky Component

Step 1 Take a section and a plan drawing of the room, drawn to any scale. Mark reference points on the drawings, usually a regular grid of points at working plane height. Choose a protractor that is suitable for the angle of glazing and for the type of sky required.

Step 2 On the section draw sight lines from the chosen reference point to the top and bottom edges of sky visible from that point. Place the primary scale of the protractor over the section, aligned on the reference point, and read the two values of the sight lines, as shown in figure 7.5. Subtract the two readings to obtain the initial uncorrected value of sky component.

Step 3 Use the normal protractor scale to read the angles of the sight lines and average these readings to obtain the mean angle of elevation of the sky.

Step 4 On the plan draw sight lines from the same reference point to the vertical edges of the sky visible from that point. Place the auxiliary scale of the protractor over the plan, aligned on the reference point as shown in figure 7.6. Use the average angle of elevation to select the appropriate semicircular scale and read the values of the sight lines. To get a final correction factor add these readings if they are on opposite sides of the vertical; subtract the readings if they are both on the same side.

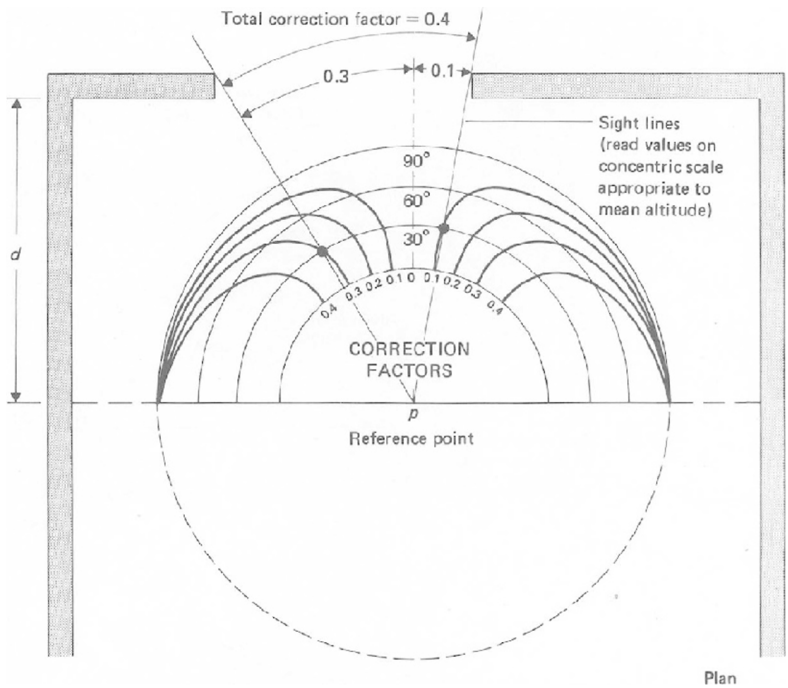


FIGURE 7.6 *BRE Daylight Protractor on plan drawing*

Step 5 The sky component for that point is equal to the initial value found in step 2 multiplied by the correction factor found in step 4.

Calculation of Externally Reflected Component The externally reflected component is initially calculated in the same manner as the sky component. Sight lines are drawn to the top edge of obstructions visible from the reference point. This gives an equivalent sky component, which is converted to the externally reflected component by allowing for the reduced luminance of the obstructing surface. For uniform sky protractors the initial ERC is divided by 10. For CIE sky protractors the initial ERC is divided by 5.

Calculation of Internally Reflected Component The internally reflected component of daylight inside a room depends on the reflectances of the room surfaces and on the size of the windows and obstructions. The process of multiple reflections is complex but formulas and tables are available to calculate the IRC. Table 7.2 gives a simplified example.

TABLE 7.2 *Internally reflected components**

Window area as % of floor area	Floor reflection factor (10%)				Floor reflection factor (40%)			
	Wall reflection factor							
	(20%)	(40%)	(60%)	(80%)	(20%)	(40%)	(60%)	(80%)
5	0.1	0.1	0.2	0.4	0.1	0.2	0.4	0.6
10	0.1	0.2	0.4	0.7	0.3	0.5	0.8	1.2
20	0.2	0.5	0.8	1.4	0.5	0.9	1.5	2.3
30	0.3	0.7	1.2	2.0	0.8	1.3	2.1	3.3
40	0.5	0.9	1.6	2.6	1.0	1.7	2.7	4.2
50	0.6	1.1	1.9	3.1	1.3	2.1	3.2	4.9

* This table gives the *minimum* IRC values for rooms of approx. 40 m^2 floor area, 3 m height, 70 per cent ceiling reflection factor and with window on one side.

Source: Adapted from *BRE Digest 42*.

*   *   *   *   *

Worked example 7.2

Calculate the sky component for the room and reference point illustrated in figures 7.5 and 7.6. Use the readings shown on the protractors.

Step 1 The drawings of the room and the reference point are shown in figures 7.5 and 7.6. The protractor is type number 2, for vertical glazing and a CIE sky.

Step 2 Primary scale:

top reading	11
subtract bottom reading	0.5
Uncorrected sky component	10.5 per cent

Step 3 Elevation scale

top reading	50 °
bottom reading	10 °
Average angle of elevation	60/2 = 30 °

Step 4 Auxiliary scale

first reading	0.3
second reading	0.1
Correction factor	0.4

Step 5

Sky component = Uncorrected sky component x correction factor

= 10.5 x 0.4 = 4.2

Sky component = **4.2 per cent**

* * * * *

COMBINED LIGHTING

People prefer to work by natural light but it is difficult to provide adequate levels of natural illumination to all parts of an interior. Even areas quite close to windows may need extra illumination for some purposes and artificial lighting then needs to be combined with the natural lighting. This system of combined lighting needs careful design so as to preserve the effect of daylight as much as possible, and to make the best use of energy.

PSALI

PSALI is an abbreviation for *permanent supplementary artificial lighting of interiors.*

PSALI is a system of combined daylighting and artificial lighting where parts of an interior are lit for the whole time by artificial light, which is designed to balance and blend with the daylight.

The use of PSALI retains most of the psychological benefits of full daylighting but allows the use of deeper room plans, which can save energy because of lower heat losses. The guiding principle of PSALI is to provide illumination that *appears* to be of good daylight character, even though most of the working illumination might be supplied by unobtrusive artificial light sources.

To achieve an appropriate blend of lighting the following factors should be considered.

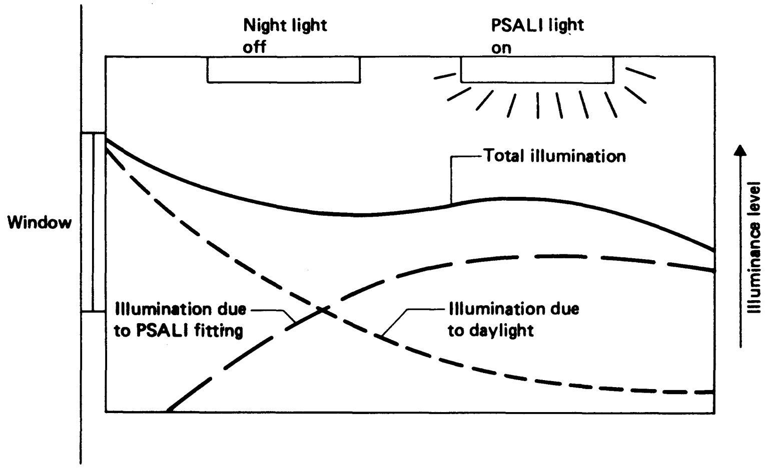


FIGURE 7.7 *Example of PSALI system*

Distribution of Light The total illuminance should gradually increase towards the windows. The illumination to be provided by PSALI can be determined by choosing a final illumination curve, as shown in figure 7.7, and then subtracting average daylight values. The illuminance over the main working areas should not vary by more than about 3 to 1.

Sudden changes in luminance between room surfaces should be avoided. In general this requires neutral colour schemes, which have the same appearance under both natural and artificial light.

Choice of Lamps The lamps chosen for the artificial lighting should match the natural light in colour appearance. Daylight is variable in colour quality, with a different spectral output to any lamp, so a compromise must be made. Tubular fluorescent lamps with colour temperatures in the range 4000 – 6500 K are usually employed for PSALI. The fittings should be unobtrusive and are often recessed in the ceiling.

Switching A combined lighting system requires several lighting control circuits – for the PSALI during daylight hours and for the complete artificial lighting after dark. Figure 7.7 indicates a simple system where extra lights would be switched on at night or during dull days. Some types of building can save electrical energy by controlling the artificial lighting with photo-electric cells which sense changing daylight levels and switch lights on and off as necessary.

EXERCISES

1 Calculate the luminance of a CIE standard sky at an altitude of 20° if the luminance at the zenith is taken to be 2200 cd/m^2.
2 The natural illuminance at a point inside a room is 430 lx and the illuminance given by an unobstructed sky is assumed to be 5380 lx. Calculate the daylight factor at that point.
3 Draw a plan of a convenient classroom or office and sketch the shapes of the daylight factors that would be expected from the windows. If possible, investigate the actual distribution of daylight with a light meter.

ANSWERS

1 1235 cd/m^2
2 8 per cent

8 Principles of Sound

Good building design invariably involves a consideration of the presence of sound in the environment. Common topics of concern are the exclusion of external noise, the reduction of sound passing between rooms and the quality of sound inside rooms. Before these topics are studied, this chapter outlines the basic principles of sound and its measurement.

NATURE OF SOUND

Origin of sound

Sound is a sensation produced in the ear by variations in the pressure of the air. These pressure variations transfer energy from a source of vibration. Air can be vibrated by a variety of methods as shown in the following examples:

1. *Moving objects* Examples: loudspeakers, guitar strings, wall panels and human vocal chords.
2. *Moving air* Examples: horns, organ pipes, mechanical fans and jet engines.

A vibrating object compresses adjacent particles of air as it moves in one direction and leaves them spread out as it moves in the other direction. This is illustrated in figure 8.1. The displaced particles pass on their extra energy and a pattern of compressions and rarefactions travels out from the source while the individual particles return to their original positions.

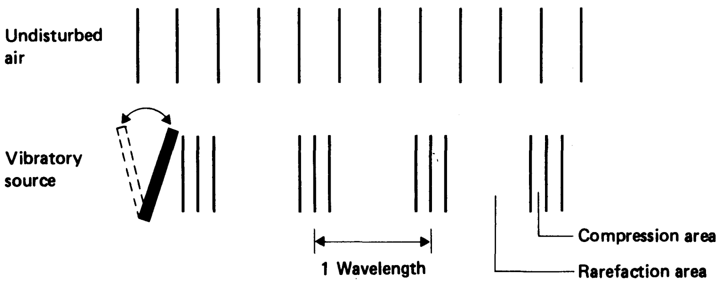


FIGURE 8.1 *Pressure variations in a sound wave*

Wave motion

Although the individual particles of air return to their original position the sound energy obviously travels forward and does so in the form of a wave motion. The front of the wave spreads out equally in all directions unless affected by an object or another material in its path.

The waves are *longitudinal* in type because the particles of the medium carrying the wave vibrate in the direction of travel of the wave, as shown in figure 8.1. The sound waves can travel through solids, liquids and gases, but not through a vacuum.

It is difficult to depict a longitudinal wave in a diagram so it is convenient to represent it as shown in figure 8.2, which is a plot of the vibrations against time. For a pure sound of one frequency, as in figure 8.2, the plot takes the form of a sine wave.

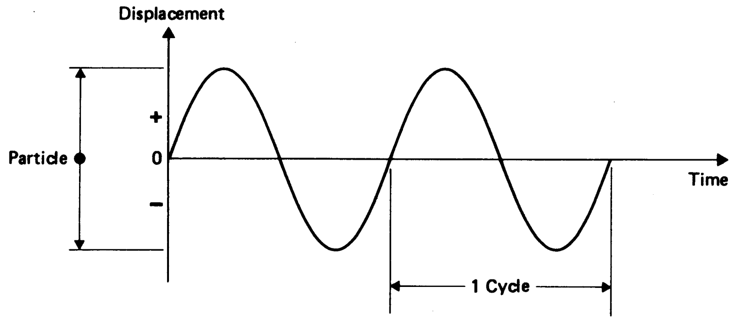


FIGURE 8.2 *Vibrations of a sound wave*

Sound waves are like any other wave motion and can be specified in terms of wavelength, frequency and velocity.

WAVELENGTH (λ) is the distance between any two repeating points on a wave.

UNIT: metre (m).

In figure 8.1 a wavelength is shown measured between two compressions but the length between any two repeating points would be the same.

FREQUENCY (*f*) is the number of cycles of vibration per second.

UNIT: hertz (Hz).

Figure 8.2 shows two complete vibrations, or cycles.

VELOCITY (*v*) is the distance moved per second in a fixed direction.

UNIT: metres per second (m/s).

For every vibration of the sound source the wave moves forward by one wavelength. The number of vibrations per second therefore indicates the total length moved in 1 s – which is the same as velocity. So that

$$\boxed{v = f \times \lambda}$$

where

v = velocity in m/s

f = frequency in Hz

λ = wavelength in m

*　　*　　*　　*　　*

Worked example 8.1

A particular sound wave has a frequency of 440 Hz and a velocity of 340 m/s. Calculate the wavelength of this sound.

v = 340 m/s, f = 440 Hz, λ = ?

Using

$$v = f \times \lambda$$

$$340 = 440 \times \lambda$$

$$\lambda = \frac{340}{440} = 0.7727$$

Wavelength = **0.7727 m**

*　　*　　*　　*　　*

Velocity of sound

A sound wave travels from its source with a steady velocity that is independent of the rate at which the vibrations occur. This means that the frequency of a sound does not affect its speed.

The velocity of sound is affected by the properties of the material through which it is travelling. The velocity in air increases as the temperature or humidity increases. It is, however, unaffected by variations in atmospheric pressure such as those caused by the weather. An indication of the velocities of sound in different materials is given in table 8.1.

TABLE 8.1 *Velocity of sound*

Material	Typical velocity (m/s)
Air (0 °C)	331
Air (20 °C)	344
Water (25 °C)	1498
Pine	3300
Glass	5000
Iron	5000
Granite	6000

Sound travels faster in liquids and solids than it does in air because the densities and elasticities of those materials are greater. The particles of such materials respond to vibrations more quickly and so convey the pressure vibrations at a faster rate.

Frequency of sound

If an object that produces sound waves vibrates 100 times a second, for example, then the frequency of that sound wave will be 100 Hz. The human ear hears this as sound of a certain pitch.

PITCH is the frequency of a sound as perceived by human hearing.

Low-pitched notes are caused by low-frequency sound waves and high-pitched notes are caused by high-frequency waves. The pitch of a note determines its position in the musical scale. The frequency range to which the human ear responds is approximately 20 to 20 000 Hz and frequencies of some typical sounds are shown in figure 8.3.

Most sounds contain a combination of many different frequencies and it is usually convenient to measure and analyse them in ranges of frequencies, such as the octave.

An OCTAVE BAND is the range of frequencies between any one frequency and double that frequency.

For example, 880 Hz is one octave above 440 Hz. Octave bands commonly used in frequency analysis have the following centre frequencies:

31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000 Hz

The upper frequency of an octave band can be found by multiplying the centre frequency by a factor of $\sqrt{2}$.

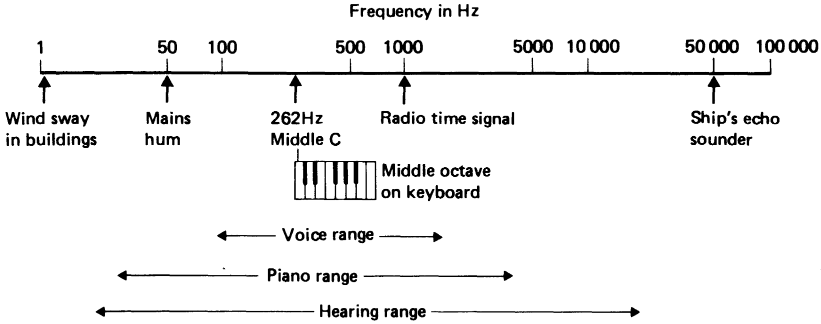


FIGURE 8.3 *Frequency ranges of sound waves*

Quality of sound

A pure tone is sound of only one frequency, such as that given by a tuning fork or electronic signal generator. Most sounds heard in everyday life are a mixture of more than one frequency, although a lowest *fundamental* frequency predominates when a particular 'note' is recognisable. This fundamental frequency is accompanied by *overtones* or *harmonics*, which are frequencies equal to whole number multiples of the fundamental.

For example, the initial overtones of the note with a fundamental of 440 Hz are as follows

440 Hz = fundamental	or	1st harmonic
880 Hz = 1st overtone	or	2nd harmonic
1320 Hz = 2nd overtone	or	3rd harmonic etc.

Different voices and instruments are recognised as having a different quality when making the same note. This individual *timbre* results because different instruments produce different mixtures of overtones which accompany the fundamental. The frequencies of these overtones may well rise to 10 000 Hz or more and their presence is often an important factor in the overall effect of a sound. A telephone, for example, transmits few frequencies above 3000 Hz and the exclusion of the higher overtones noticeably affects reproduction of the voice and of music.

Resonance

Every object has a *natural frequency* – characteristic frequency at which it tends to vibrate when disturbed. For example, the sound of a metal bar dropped on the floor can be distinguished from a block of wood dropped in the same way. The natural frequency depends upon factors such as the shape, density and stiffness of the object.

Resonance occurs when the natural frequency of an object coincides with the natural frequency of any vibrations applied to the object. The result of resonance is extra large vibrations at this frequency.

Resonance may occur in many mechanical systems. For instance, it can cause loose parts of a car to rattle at certain speeds when they resonate with the engine vibrations. The shattering of glass objects has been attributed to resonance with a singer's top note! Less dramatic, but of practical importance: resonance affects the transmission and absorption of sound in partitions and cavities.

SOUND LEVELS

The strength or loudness of a sound depends upon its energy content and this affects the pressure variations it produces. The amplitude of the sound wave, the maximum displacement of each air particle, is greater for stronger sounds – as shown in figure 8.4. Notice that the frequency of the sound remains unaltered.

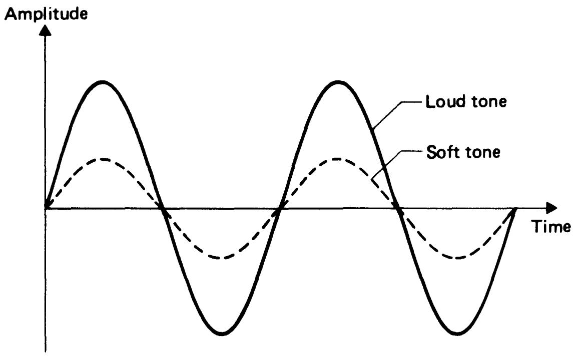


FIGURE 8.4 *Waveforms of soft and loud sounds*

Measurement

To specify the strength of a sound it is usually easiest to measure or describe some aspect of its energy or pressure. Even so, sound does not involve large amounts of energy and its effect depends upon the high sensitivity of our hearing.

> **SOUND POWER (P) is the rate at which sound energy is produced at the source.**
>
> UNIT: **watt (W).**

This is a fundamental property of a sound *source* but is difficult to measure directly. The maximum energy output of a voice is about 1 mW, which explains why talking does not usually exhaust us! In terms of sound power a typical jet engine produces only several kilowatts.

SOUND INTENSITY (I) is the sound power distributed over unit area.

UNIT: Watts per square metre (W/m^2).

This is a measure of the rate at which energy is *received* at a given surface. If, for example, a source is radiating sound in all directions the sound spreads out in the shape of a sphere and the intensity is given by

$$I = \frac{P}{4\pi r^2}$$

where

P = sound power of the source (W)

r = distance from the source (m)

I = intensity at distance (W/m^2)

SOUND PRESSURE (p) is the average variation in atmospheric pressure caused by the sound.

UNIT: pascal (Pa).

The pressure is continuously varying between positive and negative values so it is measured by its RMS (root mean square) value – a type of average which has positive values only.

RMS pressure = 0.707 maximum pressure

The intensity of a sound is proportional to the square of its pressure

$$I \propto p^2$$

Thresholds

The weakest sound that the average human ear can detect is remarkably low and occurs when the membrane in the ear is deflected by a distance less than the diameter of a single atom.

The THRESHOLD OF HEARING is the weakest sound the average human ear can detect.

The value of the threshold varies slightly from person to person but for reference purposes it is defined to have the following values at 1000 Hz

$I = 1 \times 10^{-12}$ W/m^2 when measured as intensity

$p = 20 \times 10^{-6}$ Pa when measured as pressure

The THRESHOLD OF PAIN is the strongest sound that the human ear can tolerate.

Very strong sounds become painful to the ear. Excessive sound energy will damage the ear mechanism and very large pressure waves will have other harmful physical effects, such as those experienced in an explosion. The threshold of pain has the following approximate values

$I = 1$ W/m^2 or $p = 200$ Pa

Decibels

Although it is quite accurate to specify the strength of a sound by an absolute intensity or pressure, it is usually inconvenient to do so. For instance, the range of values between the threshold of hearing and the threshold of pain is a large one and involves awkward numbers. It is also found that, for the same change in intensity or pressure, the ear hears different effects when listening at high intensities and at low intensities. The ear judges differences in sound by ratios so that, for example, the difference between 1 and 2 Pa pressure is perceived to be the same difference as between 5 and 10 Pa.

For practical measurements of sound strength it is convenient to use a decibel scale based on constant ratios, a scale which is also used in some electrical measurements.

The DECIBEL (dB) is a logarithmic ratio of two quantities.

The decibel is calculated by the formula:

$$N = 10 \log_{10} \left(\frac{I_2}{I_1} \right) = 10 \log_{10} \left(\frac{p_2}{p_1} \right)^2$$

where

N = number of decibels

I_1 and I_2 are the two intensities being compared

or

p_1 and p_2 are the two pressures being compared

Sound levels

In the measurement of sound levels the decibel ratio is always made with reference to the standard value for the threshold of hearing. This produces a scale of numbers that is convenient and gives a reasonable correspondence with the way that the ear compares sounds.

Figure 8.5 shows the total range of sound levels in decibels between the two thresholds of hearing and gives typical decibel values of some common sounds. Precise values would depend upon the frequencies of the sound and the distances from the source.

The smallest change that the human ear can detect is 1 dB, although a 3 dB change is considered the smallest difference that is generally significant. A 10 dB increase or decrease makes a sound seem approximately twice as loud or half as loud.

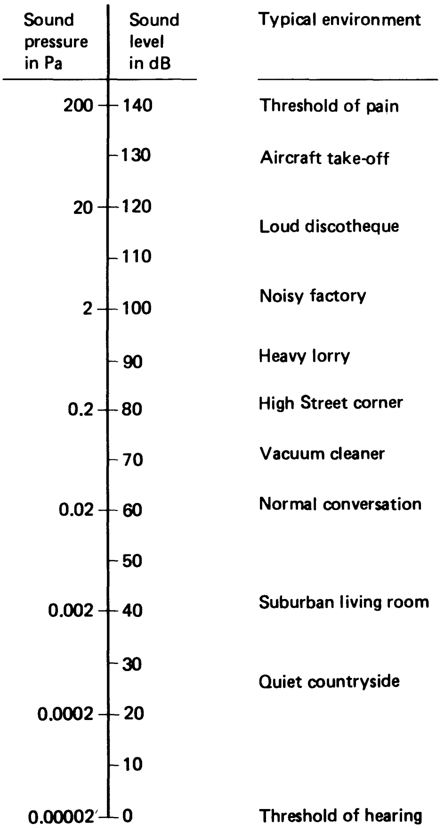


FIGURE 8.5 *Examples of sound levels*

Calculation of sound levels

Values of sound intensity or sound pressure are converted to decibels by comparing them with the standard value of the threshold of hearing. The word 'level' indicates that this reference has been used.

Sound Intensity Level If the sound strength is considered in terms of intensity then a sound intensity level (SIL) is given by the formula

$$\boxed{\text{SIL} = 10 \log_{10}\left(\frac{I}{I_0}\right)}$$

where

I = the intensity of the sound being measured (W/m^2)

I_0 = the intensity of the threshold of hearing taken as 1×10^{-12} W/m^2

Sound Pressure Level Most practical instruments measure sound by responding to the sound pressure. The sound pressure level (SPL) is then given by the formula

$$\boxed{\text{SPL} = 20 \log_{10}\left(\frac{p}{p_0}\right)}$$

where

p = the RMS pressure of the sound being measured (Pa)

p_0 = the RMS pressure of the threshold of intensity taken as 20 μPa

For practical purposes, the SIL and SPL give the same value in decibels.

* * * * *

Worked example 8.2

A sound has a pressure of 4.5×10^{-2} Pa when measured under certain conditions. Calculate the sound pressure level of this sound. Threshold of hearing pressure = 20×10^{-6} Pa.

$p = 4.5 \times 10^{-2}$ Pa, $p_0 = 20 \times 10^{-6}$ Pa, SPL = ?

Using

$$\text{SPL} = 20 \log (p/p_0)$$

$$= 20 \log \left(\frac{4.5 \times 10^{-2}}{20 \times 10^{-6}}\right) = 20 \log (2250)$$

$$= 20 \times 3.3522 = 67.04$$

SPL = **67 dB**

Worked example 8.3

Calculate the change in sound level when the intensity of a sound is doubled.

Let I = initial intensity, so $2I$ = final intensity.

Let L_1 = initial sound level and L_2 = final sound level.

$$L_2 - L_1 = 10 \log \left(\frac{2I}{I_0}\right) - 10 \log \left(\frac{I}{I_0}\right)$$

$$= 10 \log \left(\frac{2I}{I_0} \div \frac{I_0}{I}\right) \quad \text{(by the rules of logarithms)}$$

$$= 10 \log \left(\frac{2I}{I}\right) = 10 \log 2$$

$$= 10 \times 0.3010 = 3.010$$

Change in SIL = **3 dB**

* * * * *

Combination of sound levels

If two different sounds arrive at the same time then the ear is subject to two pressure waves. Because the decibel scale is logarithmic in origin the simple addition of sound levels in decibels does not give the sound level of the combined sounds. For instance, two jet aircraft each with a SPL of 105 dB do not, fortunately, combine to give a total effect of 210 dB, which is well above the threshold of pain.

Although decibels cannot be directly added, intensities can be added or the squares of pressures can be added

$$I = I_1 + I_2$$

or

$$p = \sqrt{(p_1^2 + p_2^2)}$$

* * * * *

Worked example 8.4

Calculate the total sound level caused by the combination of sound levels of 95 dB and 90 dB. Threshold of hearing intensity = 1×10^{-12} W/m^2.

Let I_1 = intensity of 95 dB, I_2 = intensity of 90 dB, and I_3 = intensity of combined sounds.

Using

$$\text{SIL} = 10 \log (I/I_0)$$

$$95 = 10 \log \left(\frac{I_1}{I_0}\right) \quad \text{and} \quad 90 = 10 \log \frac{I_2}{I_0}$$

$$\log \left(\frac{I_1}{I_0}\right) = \frac{95}{10} \qquad \log \left(\frac{I_2}{I_0}\right) = \frac{90}{10}$$

$$\frac{I_1}{I_0} = \text{antilog } 9.5 \qquad \frac{I_2}{I_0} = \text{antilog } 9$$

$$\frac{I_1}{1 \times 10^{-12}} = 3.16 \times 10^9 \qquad \frac{I_2}{1 \times 10^{-12}} = 1 \times 10^9$$

$$I_1 = 3.16 \times 10^9 \times 10^{-12} \qquad I_2 = 1 \times 10^9 \times 10^{-12}$$

$$I_1 = 3.16 \times 10^{-3} \text{ W/m}^2 \qquad I_2 = 1 \times 10^{-3} \text{ W/m}^2$$

$$I_3 = I_1 + I_2$$

$$= (3.16 \times 10^{-3}) + (1 \times 10^{-3}) = 4.16 \times 10^{-3}$$

$$\text{Combined SIL} = 10 \log \left(\frac{I_3}{I_0}\right) = 10 \log \left(\frac{4.16 \times 10^{-3}}{1 \times 10^{-12}}\right)$$

$$= 10 \log (4.16 \times 10^9)$$

$$= 10 \times 9.619$$

Total Sound Level = **96 dB**

* * * * *

The addition of decibel values is made easier with the aid of a table such as that in figure 8.6. The fact that the ear cannot detect differences less than 1 dB makes the inaccuracies of the table acceptable.

Consider some of the practical implications of combining decibel values. A doubling of sound energy, such as that produced by two identical engines, produces a maximum increase of 3 dB. If the difference between two sound levels is greater than 15 dB then the addition of the lower level will produce negligible effect. This means that a sound of 80 dB, for example, will not be heard above another sound of 95 dB; unless the two sounds have very different frequency contents.

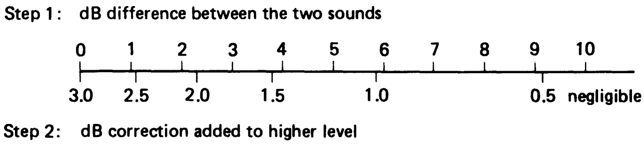


FIGURE 8.6 *Addition of sound levels*

ATTENUATION OF SOUND

As sound waves spread out from a source they attenuate – that is, their amplitude decreases and the sound level drops. Except for some absorption by the air the total energy of the wave front remains constant but the area of the wave front constantly increases. The energy therefore spreads over larger areas and the sound intensity or sound pressure measured at any point decreases.

The manner in which the sound wave spreads and attenuates is affected by any directional effects of the source – a jet engine, for example, emits more noise to the rear than to the front. The propagation of the sound is also affected by any reflecting or blocking objects in the path.

A *free field* is one in which the sound waves encounter no objects. If there is an object in the sound path then some of the sound will be reflected, some absorbed and some transmitted through the object. The exact effects depend on the nature of the object and the wavelength of the sound. In general, the size of the object must be greater than one wavelength of the sound wave in order to significantly affect the wave.

For the initial prediction of the sound in the open air it is necessary to assume free field conditions and to consider the behaviour of sound being emitted from a point or a line type of source. These results may then be modified to take account of the conditions encountered in practical situations.

Point source of sound

In a free field the sound wave from a point source spreads out uniformly in all directions in the shape of a sphere, as shown in figure 8.7. The surface area of a

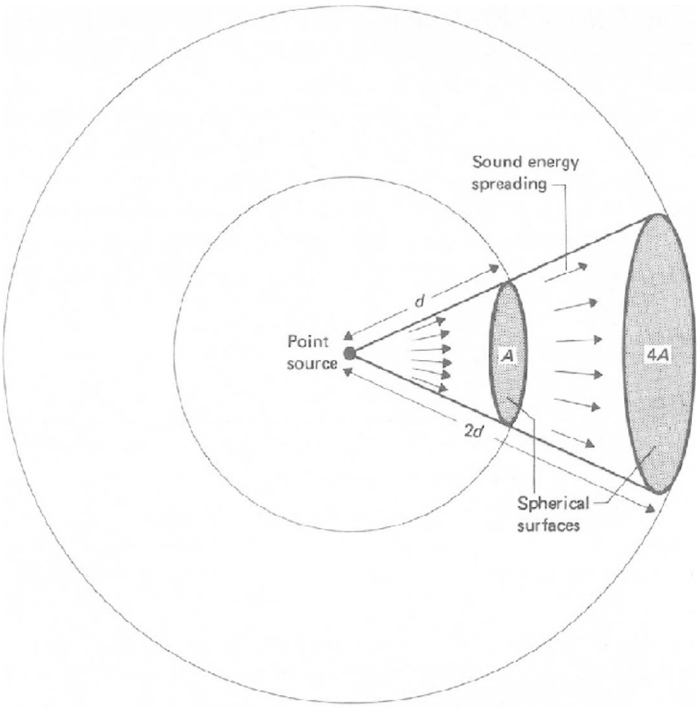


FIGURE 8.7 *Attenuation of sound from a point source*

sphere increases in proportion to the square of its radius and so the intensity of sound energy varies in an inverse manner.

Inverse Square Law

The sound intensity from a point source decreases in inverse proportion to the square of the distance from the source.

In general for a point source

$$I \propto \frac{1}{d^2}$$

where I is the sound intensity measured at distance d from the source.

The ratio of any two intensities is given by the formula

$$\boxed{\frac{I_1}{I_2} = \frac{{d_2}^2}{{d_1}^2}}$$

where I_1 is the sound intensity measured at distance d_1 from the source and I_2 is the sound intensity measured at distance d_2 from the source.

* * * * *

Worked example 8.5

A microphone measures sound at a position in a free field 5 m from a point source. Calculate the change in SPL if the microphone is moved to a position 10 m from the source.

Let L_1 = SPL at distance d_1 = 5 m, and L_2 = SPL at distance d_2 = 10 m.

Using $L_1 - L_2 = 10 \log (I_1/I_2)$, and $(I_1/I_2) = (d_2^2/d_1^2)$ gives

$$L_1 - L_2 = 10 \log \left(\frac{d_2^2}{d_1^2}\right) = 10 \log \left(\frac{10^2}{5^2}\right)$$

$$= 10 \log \left(\frac{100}{25}\right) = 10 \log 4$$

$$= 10 \times 0.6021 = 6.021$$

Change in SPL = **6 dB** decrease

* * * * *

Worked example 8.5 illustrates the general effect of attenuation from a point source of sound: the SPL decreases by 6 dB each time the distance is doubled.

If the source is on a perfectly flat and reflecting surface then all the sound radiates into a hemisphere. The SPL then decreases by 3 dB when the distance is doubled. A single motor car approximates to this condition.

Line source of sound

The sound wave from a line source spreads out in the shape of a cylinder, as shown in figure 8.8. The surface area of a cylinder increases in simple proportion to its radius. Sound intensity from a line source therefore decreases in inverse proportion to the distance from the source.

In general for a line source

$$I \propto \frac{1}{d}$$

where I is the sound intensity measured at distance d from the source.

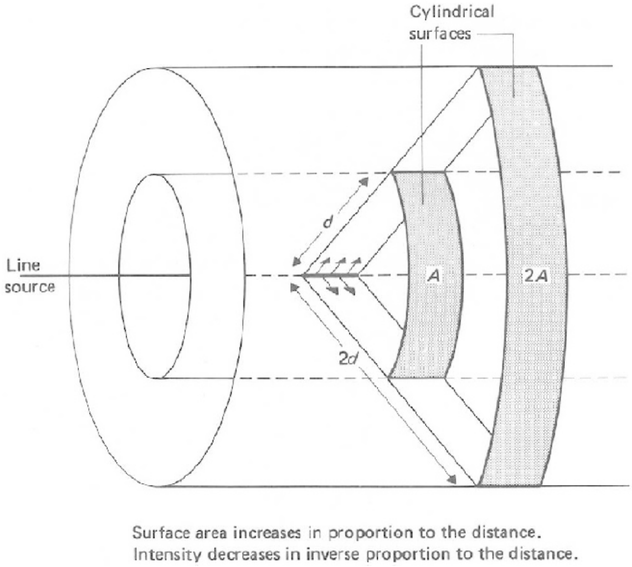


FIGURE 8.8 *Attenuation of sound from a line source*

The ratio of any two intensities is given by the formula

$$\frac{I_1}{I_2} = \frac{d_2}{d_1}$$

where I_1 is the sound intensity measured at distance d_1 from the source and I_2 is the sound intensity measured at distance d_2 from the source.

For a perfect line source the SPL decreases by 3 dB each time the distance is doubled. For a line source radiating all its energy into half a cylinder the attenuation is 1.5 dB for each doubling of distance. A line of cars on a busy road may approximate to this latter condition.

Attenuation by air

The attenuation of sound caused by its spreading out from a point or line source is an effect of energy distribution. There are additional factors, which may affect the passage of sound in the open air.

Air Absorption Some of the energy of a sound wave is spent in alternately compressing and expanding air. The effect is negligible at low frequencies and at 2000 Hz causes a reduction of about 0.01 dB/m of travel. The attenuation is increased at low humidities.

Temperature Gradients The velocity of sound is greater in warm air than in cold air. Open air has layers at different temperatures and sound waves crossing these layers are deflected by the process of refraction.

One result of this refraction is that, in general, sound travels along the ground better at night than during the day. This is the effect of relative changes in the temperature of the air lying next to the ground. In the day sound is refracted upwards and at night it is refracted downwards.

Wind Effects Sound waves will be affected by any wind blowing between the source and the receiver. The velocity of wind increases with height above the ground and this gradient deflects the sound waves upwards or downwards.

Ground Attenuation It is possible for some sound energy to be absorbed by passing over the surface of the ground. This effect is quite local and only applies within 6 m of the ground, which must be free of obstructions. Hard surfaces, such as paving, provide little attenuation but surfaces such as grassland can provide a reduction of overall noise level of up to 5 dB.

NATURE OF HEARING

Sound waves are a phenomena that can be detected and measured without the aid of human senses, but the aspect of sound that interests us most is the human perception of sound waves. The sense of hearing involves the ear and the brain and the effect of sound can therefore vary from person to person. However, the basic characteristics as outlined in this section are shared by most people.

The ear

Most of the mechanism of the ear is situated inside the head and the structure of the ear can be divided into three main parts, as shown in figure 8.9.

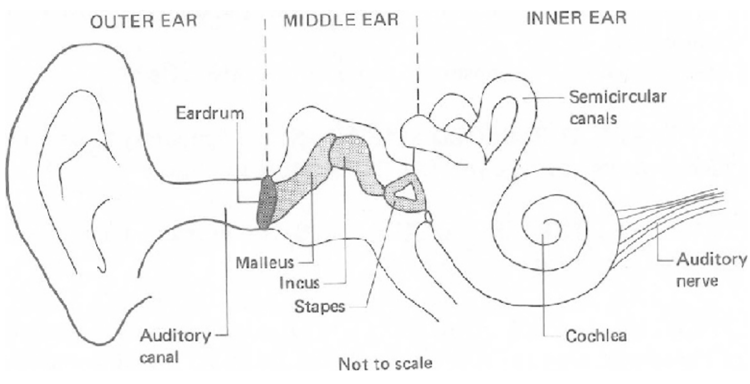


FIGURE 8.9 *The ear*

(1) *Outer Ear* The outer ear is part of the ear that can be seen. It collects the sound waves and funnels them to the ear drum, a membrane which vibrates when sound waves fall upon it.
(2) *Middle Ear* The middle ear is an air-filled cavity, connected to the throat, which passes the vibrations of the ear drum to the inner ear. This transfer is achieved by means of the three small bone levers. The mechanical link between the bones amplifies the vibrations to adjust for the difference between the air of the middle ear and the fluid of the inner ear.
(3) *Inner Ear* The inner ear converts the mechanical vibrations of sound into electrical impulses which are transmitted to the brain. The *cochlea* is a hollow coil of bone, filled with liquid, in which the sound waves vibrate. Dividing the cochlea along its length is the *basilar membrane*, which contains approximately 25 000 nerve endings. The fine hairs attached to these nerves detect the sound vibrations in the fluid and the information is transmitted to the brain by the auditory nerve. The inner ear is situated near the three semi-circular canals which contain fluid and are associated with the sense of balance.

Deafness

Loss of hearing not only affects sensitivity to sounds but also affects the frequencies at which sounds can be detected. The various causes of deafness can be broadly categorised as follows:

Middle Ear Deafness This type of deafness is a result of a stiffening of the system of connecting bones. It may be caused by various infections or by a broken ear drum. The resulting deafness affects the transmission of low tones rather than high tones and can usually be cured by drugs or by surgery.

Nerve Deafness Nerve deafness is a result of damage to the nerve endings in the inner ear or to the nerve carrying information to the brain. This type of deafness can be caused by infections, by head injuries and by exposure to high levels of noise.

The deafness caused by exposure to noise can give two effects

TEMPORARY THRESHOLD SHIFT (TTS) is a temporary loss of hearing which recovers in 1–2 days after the exposure to noise.

PERMANENT THRESHOLD SHIFT (PTS) is a permanent loss of hearing caused by longer exposure to noise.

The first effect of nerve deafness caused by exposure is loss of hearing in the region of high tones, around 4000 Hz. This does not affect speech reception at first and the deafness usually remains unnoticed until it begins to affect ordinary conversation. Because the receptor cells in the inner ear are damaged this type of deafness is irreversible and cannot be helped by amplification.

Presbyacusis This type of deafness is a gradual loss of hearing sensitivity due to age and is experienced by everybody. The higher frequencies are affected first but the effect is not usually noticeable until the age of 65 years or above. However, loss of hearing caused by age adds to any loss of hearing due to noise exposure earlier in life and the combination of the two may be noticeable.

Loudness

As the intensity of a sound increases it is heard to be 'louder'. This sensation of loudness is a function of the ear and the brain and it depends upon the frequency as well as the amplitude of the sound wave. Human hearing is not equally sensitive at all frequencies and tones of different pitch will be judged to be of different loudness, even when their SPL is the same. For example, a 50 Hz tone must be boosted by 15 dB so as to sound equally loud as a 1000 Hz tone at 70 dB.

The results of many measurements of human hearing response can be presented in the form of standard contours, as in figure 8.10. The contours show how the SPL in dB of pure tones needs to change to create the same sensation of loudness when at different frequencies. It can be seen that the ear is most sensitive in the frequency range between 2 kHz and 5 kHz, and

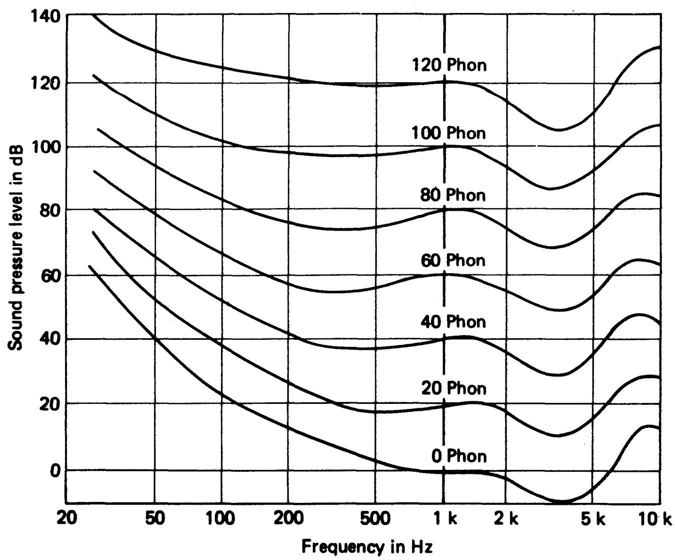


FIGURE 8.10 *Equal loudness contours*

least sensitive at low frequencies or at extremely high frequencies. This effect is more pronounced at low SPLs than at high SPLs and figure 8.10 has a 'family' of curves for different SPLs.

Phon scale

If two different tones seem equally loud to the ear then it can be useful to have a scale which gives them the same value, even though the two tones have different SPLs. The *phon* scale of loudness level is obtained from the family of equal loudness curves shown in figure 8.10.

LOUDNESS LEVEL (L_N) of any sound is numerically equal to that SPL, in decibels, of a 1000 Hz pure tone which an average listener judges to be equally loud.

UNIT: phon.

For example it can be seen from figure 8.10 that

60 phons = 60 dB at 1000 Hz

but

60 phons = 78 dB at 50 Hz

The *sone* scale of loudness is a re-numbering of the phon scale so that the sone values are directly proportional to the magnitude of the loudness. For example, 2 sones is twice as loud as 1 sone. One sone is equivalent to 40 phons. Loudness, in sones, is doubled each time the loudness level is increased by 10 phons.

EXERCISES

1 A certain sound has an intensity of 3.16×10^{-4} W/m^2. Calculate the sound intensity level in decibels if the threshold of hearing reference intensity is 1×10^{-12} W/m^2.

2 Calculate the actual pressure of a sound which has an SPL of 72 dB. Threshold of hearing reference pressure is 20×10^{-6} Pa.

3 Calculate the total sound pressure level caused by the combination of sounds with the following SPLs:
(a) 85 dB and 87 dB;
(b) 90 dB and 90 dB and 90 dB.

4 The intensity of a point source of sound, measured at a distance of 6 m from the source, is 3.4×10^{-6} W/m^2.
(a) Calculate the intensity of the sound at a distance 20 m from the source.

(b) Calculate the decibel change between the two positions.

5 Calculate the difference between SPLs measured at 10 m and at 63 m from a perfect line source of sound. State the factors that might modify this result in a practical situation.

ANSWERS

1 85 dB
2 0.0796 Pa
3 89.1 dB
94.7 dB
4 3.06×10^{-7} W/m^2
10.5 dB
5 8 dB

9 Noise

Noise is unwanted sound. This is an environmental definition of sound that takes account of the effect of a sound rather than its nature. Even if a sound consists of the finest music it can be considered as noise if it is the middle of the night!

Many of the reasons for not wanting a particular sound can be identified by the effects that it can have on the listener or on the environment. Some of these effects are described below:

1. Loss of hearing is one result of excessive exposure to noise and is discussed in chapter 8.
2. Quality of life in general decreases in a noisy environment, such as in areas near busy roads or airports.
3. Interference with desirable sounds such as speech or music can be annoying and, in some situations, dangerous.
4. Distraction from a particular task can be a result of noise and can cause inefficiency and inattention.
5. Expenses are incurred by the measures needed to try and combat noise. Businesses may suffer loss of revenue in a noisy environment.

MEASUREMENT OF NOISE

The acceptance of noise by people obviously depends on individual hearing sensitivity and living habits. The acceptance of noise is also affected by the external factors that are now outlined below:

1. *Type of environment* Acceptable levels of average noise are affected by the type of activity. A library, for example, has different requirements to those for a workshop.
2. *Frequency structure of the noise* Some frequencies are found to be more annoying or more harmful than others. For example, some types of jet engine have a more penetrating sound than others.
3. *Duration of the noise* A short exposure to a high noise level is less likely to annoy or to damage the hearing than a longer exposure.

The measurement of noise must take these factors into account and the scale used to assess them should be appropriate to the type of situation. A number of different scales have evolved and this section describes the ones in common use.

Sound level meter

A sound level meter is an instrument designed to give constant and objective measurements of sound level. Figure 9.1 shows the main sections of a typical sound level meter. Basically, the meter converts the variations in air pressure to variations of voltage which are amplified and displayed on an electrical meter calibrated in decibels. Sound level meters can be small enough to be hand-held and are supplied in several grades of accuracy.

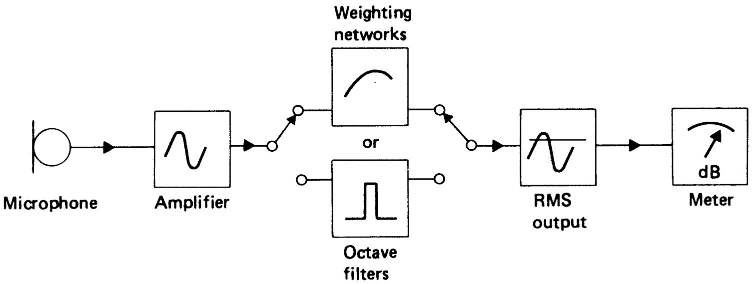


FIGURE 9.1 *Construction of a sound level meter*

A standard sound level meter takes an RMS (root mean square) value of the signal – this is a type of average which is found to be more relevant than peak values. The meter may have 'fast' and 'slow' response settings but will not be fast enough to accurately record an impulse sound, such as gunfire.

The treatment of frequencies needs special consideration, particularly in view of the non-linear response of the ear to frequency, as explained in the section on hearing.

Weighting Networks One method of dealing with the frequency content of sound is for the sound level meter to give weight to the same frequencies that human hearing emphasises. The weighting networks in a meter are electronic circuits whose response to frequency is similar to that of the ear. The response to low frequencies and to very high frequencies is reduced in a specified manner and four different weightings have been standardised internationally as the A, B, C and D scales.

The *A scale* has been found to be the most useful weighting network. Many measurements of noise incorporate decibels measured on the A scale and the symbols dB(A) indicate a standard treatment of frequency content.

Frequency Bands A sound level measurement that combines all frequencies into a single weighted reading is not suitable when it is necessary to measure particular frequencies. Some sound level meters allow the use of filters, which pass selected frequencies only. The sound pressure level (SPL) in decibels is then measured over a series of frequency bands, usually octaves or one-third octaves.

The *noise spectra* produced by such a series of measurements can be presented as a dB-frequency diagram, like that shown in figure 9.2. Narrower frequency bands give more information about the frequency content of the sound than wide frequency bands.

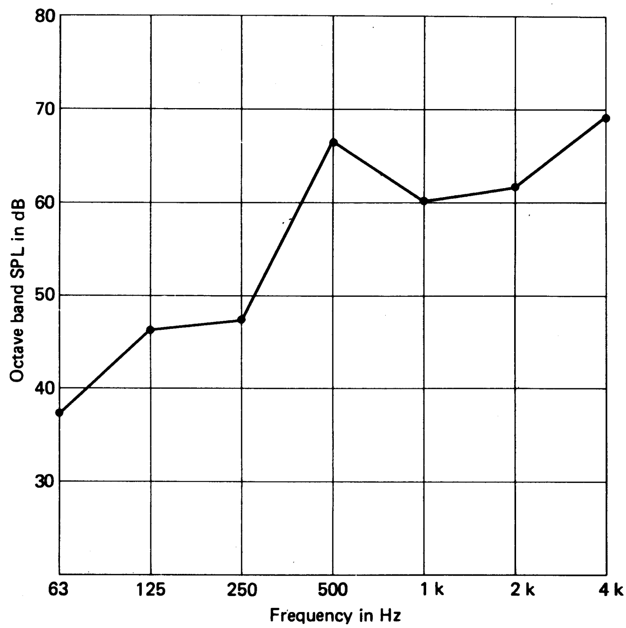


FIGURE 9.2 *Noise spectrum of telephone bell*

Noise limiting curves

One method of specifying acceptable levels of sound at different frequencies is to use standard curves of noise. These rating curves, which are plots of SPL against set frequencies, are based on the sensitivity of the human ear. The noise being analysed is measured at octave intervals, the results plotted and then compared with the standard curves, as shown in figure 9.3.

An index which rates the noise may be read from the curves. The main systems of curves are as follows:

1. NC curves, which give a noise criterion (NC);
2. PNC curves, which give a preferred noise criterion (PNC);
3. NR curves, which give a noise rating (NR)

The NC curves have been widely used for assessing the noise made by heating and ventilating equipment, and PNC curves are a development of the NC curves. NR curves are commonly used for other industrial measurements of noise.

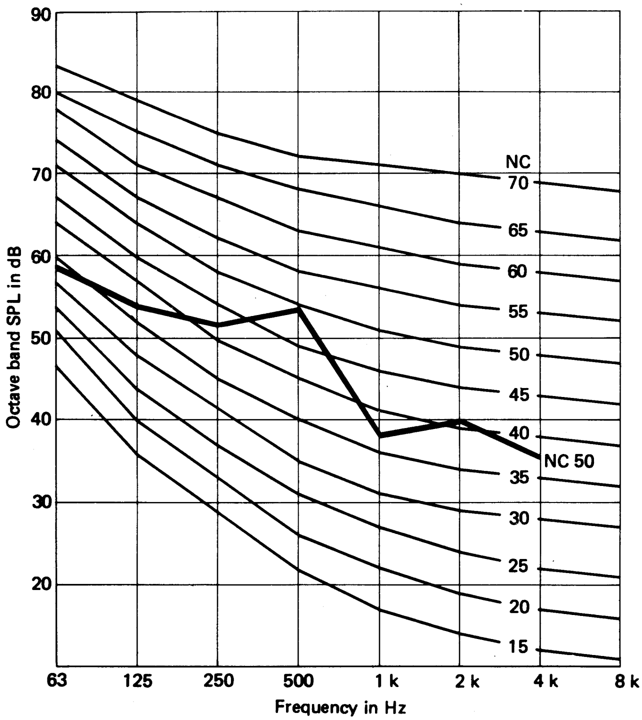


FIGURE 9.3 *NC (noise criterion) curves*

Acceptable noise limits for different purposes can be specified by numbers read from the curves and table 9.1 indicates some typical limits for levels of background noise caused by services installations.

TABLE 9.1 *Acceptable levels of background noise from services installations*

Environment	NC/NR/PNC approx. index
General offices	40
Libraries	35
Homes, Hospitals	30
Theatres, Cinemas	25
Concert halls, Studios	20

Traffic noise level

Noise caused by traffic continually changes in level and the way it varies has a considerable effect on the nuisance it causes. The traffic noise index, L_{10}, takes these variations into account.

TRAFFIC NOISE LEVEL (L_{10}) is the sound level which is exceeded for 10 per cent of a given time.

UNIT: dB(A).

L_{10} can be defined for a variety of time periods and the index used for the assessment of road traffic noise is an average of the 18 hourly L_{10} values taken between 06.00 and 24.00 hours on a normal weekday. This index has been found to give reasonable agreement with the dissatisfaction caused by road traffic noise.

L_{10} is a statistical type of measurement and is best made by a distribution analyser attached to the sound level meter. This analyser records the proportion of time the noise level has spent in each portion of the decibel scale and a typical set of results could give a plot like that shown in figure 9.4. Measurements of L_{10} must be taken at certain standard distances from the roadway with corrections made for any wind and reflections.

A typical measurement at 10 m from the edge of a motorway is L_{10} (18 hour) = 74 to 78 dB(A). One basis of Government compensation for houses affected by new or improved roads is L_{10} (18 hour) = 68 dB(A).

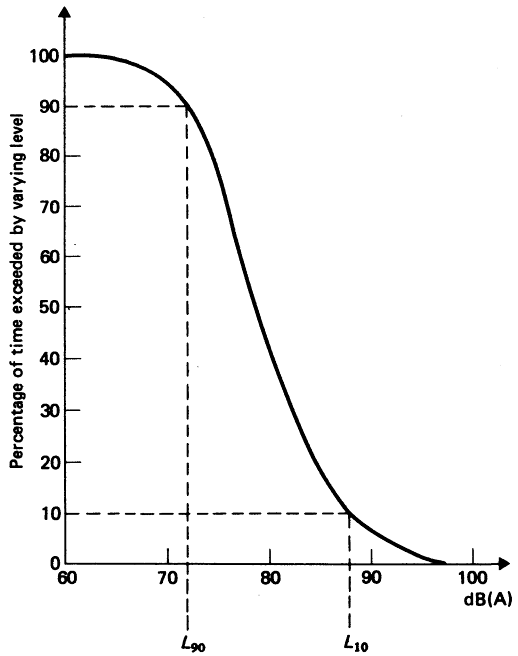


FIGURE 9.4 *Time distribution of noise level*

Equivalent continuous sound level

Another method of assessing noise that varies in level is to take a type of average – the equivalent continuous sound level, L_{eq}.

> **L_{eq} is that continuous sound level which gives the same total sound energy as the varying sound level.**
>
> UNIT: dB(A).

In a simple example, a doubling of sound energy increases the SPL by 3 dB, so that the following combinations of sound levels and time periods could give the same L_{eq}.

	90 dB(A)	for	8 hours	
or				
	93 dB(A)	for	4 hours	L_{eq} (8 hour) = 90 dB(A)
or				
	99 dB(A)	for	1 hour	

In practical situations the noise levels tend to vary continuously and special calculations, or dose meters, are used to measure the total exposure in terms of L_{eq}. The risk of damage to hearing is largely dependent on the total energy reaching the ear in a given period and L_{eq} is used in many countries to specify maximum safe *noise doses.*

Recommended levels are usually in the range L_{eq} (8 hour) = 80 to 90 dB(A). Many industries still have environments that expose people to values of L_{eq} greater than these levels.

Other noise measurements

Perceived Noise Level (L_{PN}) L_{PN} is an index of aircraft noise that takes account of those higher frequencies in aircraft engine noise which are known to cause annoyance. The noisiness is rated in *noys* and converted by calculation to perceived noise decibels PNdB.

Noise and Number Index (NNI) NNI is an index of aircraft noise that includes the average perceived noise level and the *number* of aircraft heard in a given period. This index has been used to predict and to measure annoyance resulting from noise near airports. It has also been used as the basis for the award of compensation payments to householders for sound insulation.

Speech Interference Level (SIL) SIL is a measure of the level of background noise at which the noise will interfere with speech in a particular situation. The type of voices and distances involved are taken into account.

NOISE CONTROL

There are many types of noise which cause annoyance in buildings but in general there are three types of area where action may help to reduce noise levels:

1. the sound source;
2. the sound path;
3. the receiver.

All three approaches are relevant to the design of quieter buildings, which is the concern of this chapter. However, it should be remembered that the design of vehicles, and the siting of industries, roadways and airports are factors which will also affect noise levels inside buildings.

Sound transfer

The transfer of noise within buildings is affected by the type of sound involved and it is necessary to classify the many possible sounds as being of two main types: airborne and impact sound.

> **AIRBORNE SOUND is sound which travels through the air before reaching a partition.**

The transfer of airborne sound is shown in figure 9.5 and typical sources of airborne sound include voices, radios, musical instruments, traffic and aircraft noise.

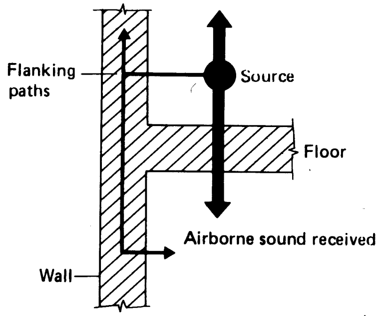


FIGURE 9.5 *Airborne sound transmission*

> **IMPACT SOUND is sound which is generated *on* a partition.**

The transfer of impact sound is shown in figure 9.6 and typical sources of impact sound include footsteps, slammed doors and windows, noisy pipes and

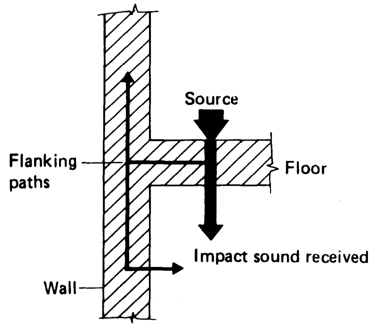


FIGURE 9.6 *Impact sound transmission*

vibrating machinery. A continuous vibration can be considered as a series of impacts and impact sound is also termed *structure-borne sound*.

It is important to distinguish between airborne and impact sound as the best methods of controlling them can differ. A single source of noise may also generate both types of sound so the definition of airborne and impact sound must be applied to the sound which is being heard in the receiving room. For example, footsteps on a floor would be heard mainly as impact sound in the room below but as airborne sound in the room above.

Sound can also pass into a receiving room by *flanking transmission*, as shown in figures 9.5 and 9.6. These indirect sound paths can be numerous and complex. The effect of flanking transmissions increases at high levels of sound insulation and often limits the overall noise reduction possible.

Absorption and insulation

The techniques used to control sound are described by some terms that may appear to be interchangeable but are, in fact, very different in their effect. Incorrect understanding of these terms leads to incorrect and wasted efforts in the control of sound.

SOUND INSULATION is the reduction of sound energy transmitted into an adjoining air space.

Insulation is the most useful method for controlling noise in buildings and is discussed in the next section.

SOUND ABSORPTION is a reduction in the sound energy reflected by the surfaces of a room.

Absorption has little effect on noise control but has an important effect on sound *quality*, which is discussed in chapter 10.

It can be shown by calculation that if the amount of absorption in a room is doubled then the sound energy in the room is halved, but the sound level drops by only 3 dB. Such a change in absorption may, however, make a difference to the subjective or apparent sound level in the room, which is influenced by the acoustic quality.

Sound absorption can also be useful in the control of noise, which spreads by reflections from the ceiling of offices and factories, or by multiple reflections along corridors or ducts as shown in figure 9.7.

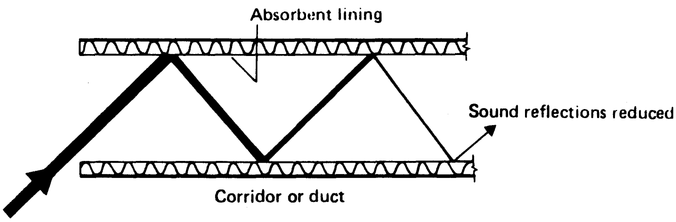


FIGURE 9.7 *Noise control by absorption*

SOUND INSULATION

Insulation is the principle method of controlling both airborne and impact sound in buildings. The overall sound insulation of a structure depends upon its performance in reducing the airborne and impact sound transferred by all sound paths, direct and indirect. The assessment of sound insulation usually considers one type of sound transfer at a time.

Sound reduction index

The difference in sound levels on either side of a partition, as shown in figure 9.8, can be used as an index of airborne sound insulation.

> **SOUND REDUCTION INDEX (SRI) is a measure of the insulation against the direct transmission of airborne sound.**

The measurement of an SRI can be made in a special laboratory where no flanking sound paths are possible around the partition under test. The sound levels in the rooms on each side of the partition are measured and a *normalised* SRI obtained by adjusting for the area of the partition and for the absorption in the receiving room.

Because insulation varies with frequency, the SRI is measured at $\frac{1}{3}$ octave

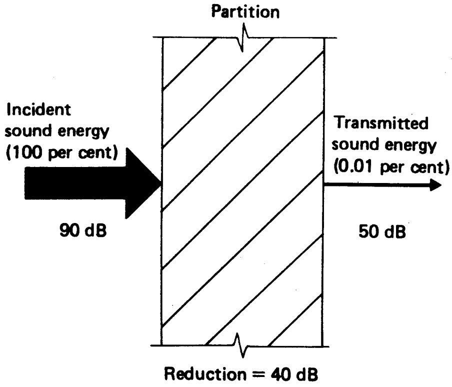


FIGURE 9.8 *Airborne sound insulation*

intervals between 100 Hz and 3150 Hz and then plotted against frequency, as shown in figure 9.9. The arithmetic average of these SRIs is usually similar to the single value measured at 500 Hz and this average value is often convenient for initial calculations. Some typical average SRIs are quoted in table 9.2 and the calculation of such insulation values is treated later in the chapter.

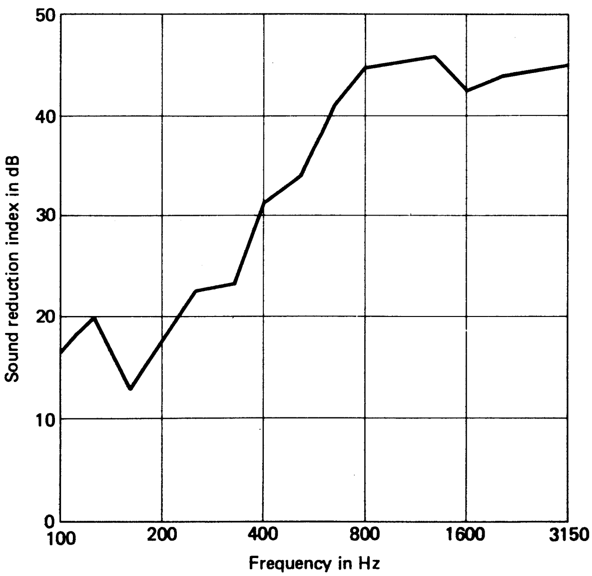


FIGURE 9.9 *An insulation curve for double glazing*

TABLE 9.2 *Sound insulation values*

Construction	Surface mass nominal (kg/m^2)	SRI 100–3010 Hz average (dB)
Walls		
255 mm brick/cavity/brick, plastered, wire ties	425	53
215 mm brickwork, plastered	425	50
102.5 mm brickwork, plastered	215	45
100 mm dense concrete	230	45
300 mm lightweight concrete	190	42
50 mm dense concrete	115	40
12 mm plasterboard and plaster	12	25
Windows		
Double, 150–200 mm air gap, sealed*		40 max.
Single, 12 mm glass, sealed*	30	30
Single, 6 mm glass, sealed*	15	25
Single, unsealed		20
Any window, open		10 approx.

* Sealed means fixed; or openable but weather-stripped.

Insulation principles

Good sound insulation depends upon the following general principles:

(1) mass;
(2) completeness;
(3) stiffness;
(4) isolation.

The effectiveness of each technique of insulation can differ with the type of sound but in most constructions all the principles are relevant. The principles are described in the following sections.

Mass

Heavyweight structures transmit less sound than lightweight structures. This is because the sound waves in dense materials have vibrations of low amplitude and so the sound that is re-radiated into the air is of low amplitude.

THE MASS LAW: The sound insulation of a single leaf partition is dependent on its mass per unit area.

Theory predicts an insulation increase of 6 dB for each doubling of mass but practical constructions give an increase in insulation of about 5 dB for each doubling of mass. So that, for example, the average SRI of a brick wall increases from 45 dB to 50 dB when the thickness is increased from 102.5 mm to 215 mm. Single-leaf construction includes composite construction on such as plastered brickwork, as long as the layers are bonded together.

Sound insulation depends upon frequency and the mass law also predicts that the sound insulation increases by about 5 dB whenever the frequency is doubled, a rise in frequency of one octave. So that, for example, a brick wall provides about 10 dB more insulation against 400 Hz sounds than against 100 Hz sounds, a rise of two octaves.

Table 9.2 gives the surface masses, or construction densities, of some structures. Where a construction does not obey the mass law it is because other factors such as airtightness, stiffness, and isolation have an effect.

Completeness

Areas of reduced insulation or small gaps in the construction of a wall have a far greater effect on overall insulation than is usually appreciated. The completeness of a structure depends upon airtightness and uniformity.

Airtightness As insulation against airborne sound is increased the presence of gaps becomes more significant. For example, if a brick wall contains a hole or crack which in size represents only 0.1 per cent of the total area of the wall, the average SRI of that wall is reduced from 50 dB to 30 dB.

Air gaps often exist because of poorly constructed seals around partitions, particularly at the joins with floors, ceilings, windows, doors, service pipes and ducts. Some materials may be porous enough to pass sound – brick and blockwork should be plastered. Doors and openable windows should be airtight when closed and the type of sealing used to increase thermal insulation is also good for sound insulation. In general, 'sound leaks' should be treated as carefully as water leaks.

Uniformity The overall sound insulation of a construction is greatly reduced by the presence of areas of poor insulation. For example, an unsealed door occupying 25 per cent of the area of a half-brick wall reduces the average SRI of that wall from 45 dB to 23 dB. The final sound insulation is influenced by relative areas but is always closer to the insulation of the poorer component than to the better component.

Windows and doors are necessary parts of a building but a knowledge of the uniformity principle may prevent effort being wasted on the insulation of the wrong areas. To improve the insulation of a composite structure the component with the lowest insulation should be improved first of all. Walls facing noisy roads should contain the minimum of windows and doors, and they should be well insulated.

Stiffness

Stiffness is a physical property of a partition and depends upon factors such as the elasticity of the materials and the fixing of the partition. High stiffness can cause loss of insulation at certain frequencies where there are resonances and coincidence effects. These upset the predictions of the mass law, as indicated in figure 9.10.

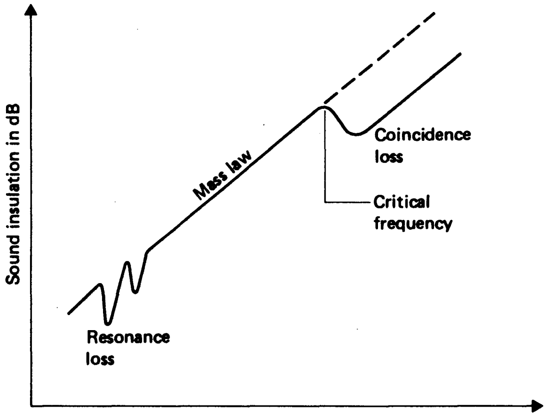


FIGURE 9.10 *Resonance and coincidence loss*

Resonance Loss of insulation by resonance occurs if the incident sound waves have the same frequency as the natural frequency of the partition. The increased vibrations that occur in the structure are passed on to the air and so the insulation is lowered. Resonant frequencies are usually low and most likely to cause trouble in the air spaces of cavity construction.

Coincidence Loss of insulation by coincidence is caused by the bending flexural vibrations, which can occur along the length of a partition. When sound waves reach a partition at angles other than 90 °, their transmission can be amplified by the flexing inwards and outwards of the partitions. The sound-wave frequency and the bending-wave frequency coincide at the *critical frequency*. For several octaves above this critical frequency the sound insulation tends to remain constant and less than that predicted by the mass law. Coincidence loss is greatest in double-leaf constructions, such as in cavity walls or in hollow blocks.

Flexible (non-stiff) materials, combined with a high mass, are best for high sound insulation. Unfortunately flexibility is not usually a desirable structural property in a wall or a floor.

Isolation

Discontinuous construction can be effective in reducing the transmission of sound through a structure. As the sound is converted to different wave motions at the junction of different materials energy is lost and a useful amount of insulation is gained. This is the principle behind the effectiveness of air cavities in windows, of floating floors, of carpets and of resilient mountings for vibrating machines. Some broadcasting and concert buildings achieve very high insulation by using the completely discontinuous construction of a double structure separated by resilient mountings.

Sound isolation is easily ruined by strong flanking transmissions through rigid links, even by a single nail. Cavity constructions must be sufficiently wide for the air to be flexible – resonance and coincidence effects can cause the insulation to be lessened at some frequencies.

Sound insulation regulations

Minimum standards of sound insulation can be defined in terms of insulation values measured at standard frequencies. These grades of insulation can be presented as curves of insulation plotted against frequency, as shown in figures 9.11 and 9.12, which represent the grades used in the Building Regulations for England and Wales.

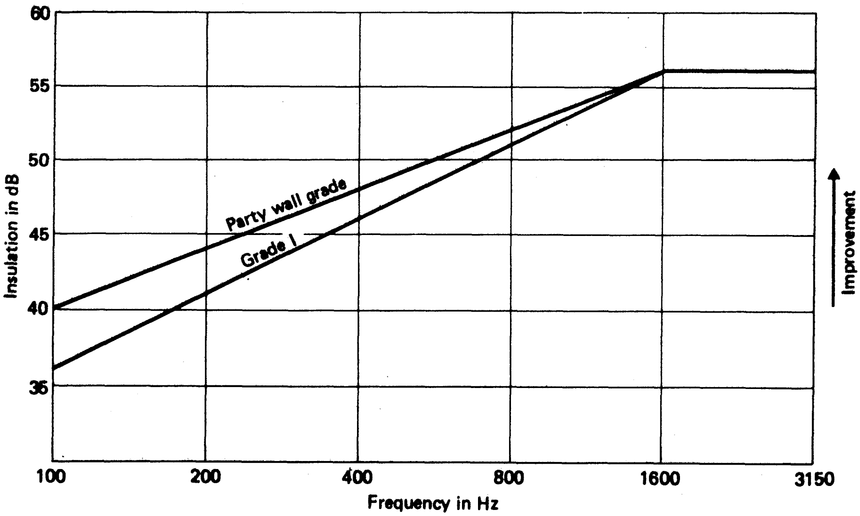


FIGURE 9.11 *Grade curves for airborne sound insulation*

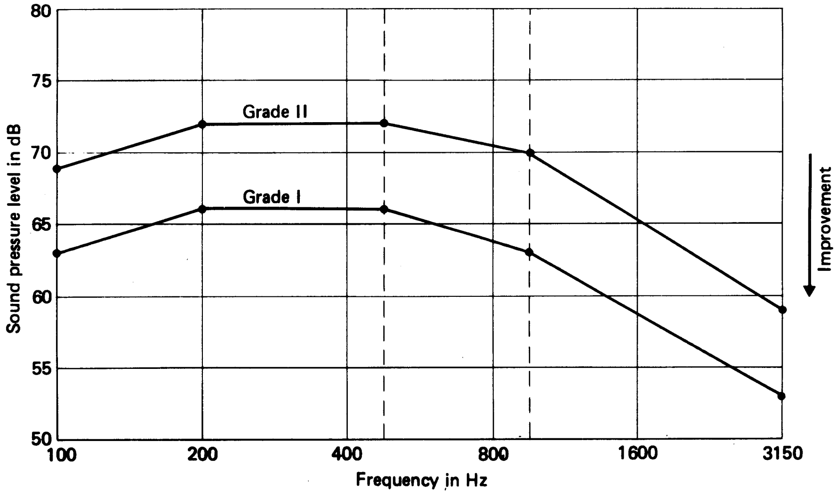


FIGURE 9.12 *Grade curves for impact sound insulation*

TABLE 9.3 *Sound insulation gradings*

Construction	Airborne sound grade	Impact sound grade
Walls		
102.5 mm brick/50 mm cavity/102.5 mm brick, pbs, 415 kg/m^2 min	Party wall	
100 mm block/50 mm cavity/100 mm block, pbs, 415 kg/m^2 min	Party wall	
215 mm brick, pbs, 415 kg/m^2 min	Party wall	
175 mm concrete – 2320 kg/m^2	Party wall	
225 mm concrete – 1600 kg/m^2, pbs*	Party wall	
200 mm concrete – 1600 kg/m^2, pbs*	Grade I	
Floors		
Concrete – 365 kg/m^2, soft finish	Grade I	Grade I
Concrete – 220 kg/m^2, floating screed	Grade I	Grade I
Concrete – 220 kg/m^2, floating wood raft	Grade I	Grade I
Floating wood floor, lath-plaster, pugging – 15 kg/m^2	Grade II	Grade II
Plain joist, lath-plaster, pugging* – 80 kg/m^2	Grade II	Grade II
Plain joist, plasterboard	Worse than Grade II	Worse than Grade II

* pbs means wall plastered on both sides. Pugging is usually sand when heavyweight and mineral wool or granules when lightweight.

To meet a particular *airborne* sound grade the insulation should be *greater* than the value shown at each frequency. To meet a particular *impact* sound grade the sound level measured beneath a floor, on which there is a standard impact generator, should be *less* than the value shown at each frequency. The insulation curves produced by actual partitions, as shown in figure 9.9, seldom follow the standard curves at every frequency and certain tolerances are allowed when grading structures. Table 9.3 lists some common types of wall and floor constructions together with the sound insulation grades that they satisfy.

The Building Regulations for England and Wales require minimum grades of sound insulation for certain walls and floors in new dwellings. In general, the walls and floors concerned are those separating one dwelling from another, or separating inhabited areas from noisy areas such as machinery rooms, corridors, and stairwells. The current requirements are outlined in table 9.4.

Insulated constructions

Figures 9.13, 9.14 and 9.15 show the details of some forms of construction that are considered to have adequate sound insulation. In each case the function

TABLE 9.4 *Sound insulation regulations for dwellings**

Partitions affected	Minimum grade	
	Airborne	Impact
Walls		
Between a dwelling and: – another dwelling – other parts of the building†	Party wall	
Between a habitable room in a dwelling and: – other parts of the building†	Party wall	
Between a habitable room in a dwelling and: – a refuse chute.	320 kg/m^2	
Between any other part of a dwelling and: – a refuse chute	220 kg/m^2	
Floors		
Between a dwelling *below* the floor and: – another dwelling, – other parts of the building†	Grade I	Grade I
Between a dwelling *above* the floor and: – other parts of the building†	Grade I	

* Summarised from Building Regulations for England and Wales 1976.† 'Other parts of a building' include areas not belonging to that dwelling; machinery and tank rooms; places used for purposes other than occasional repair or maintenance.

of certain features should be considered in terms of the principles of sound insulation explained in the previous sections.

Walls Heavy-weight walls provide good general insulation because of the mass law. Cavities can increase sound insulation by the principle of isolation but ordinary cavity walls with wire ties are little better in practice than a double skin of bricks. Light-weight walls can provide reasonable insulation if attention is paid to isolation and to the avoidance of resonances.

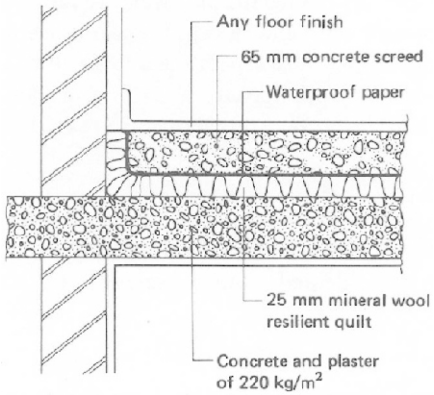


FIGURE 9.13 *Insulated concrete floor*

Floors Concrete floors need a resilient layer in order to provide insulation against impact sound. Wooden floors need to contain extra mass, such as sand pugging, to provide insulation against both airborne and impact sounds. The insulation of any floor is affected by the nature of the surrounding walls and their junctions.

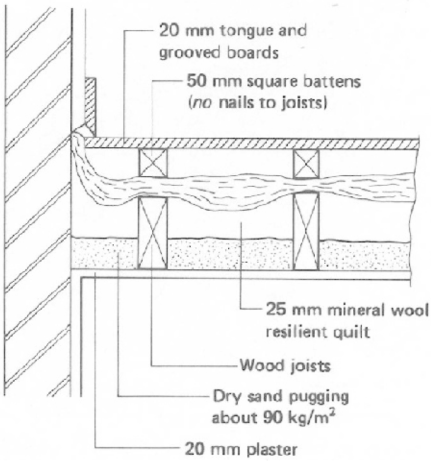


FIGURE 9.14 *Insulated wood-joist floor*

Windows Air cavities must be greater than 150 mm wide to provide worthwhile isolation and the cavity should be lined with absorbent material to minimise resonance. Heavy-weight glass provides increased sound insulation because of the mass law. Good fittings and seals provide airtightness.

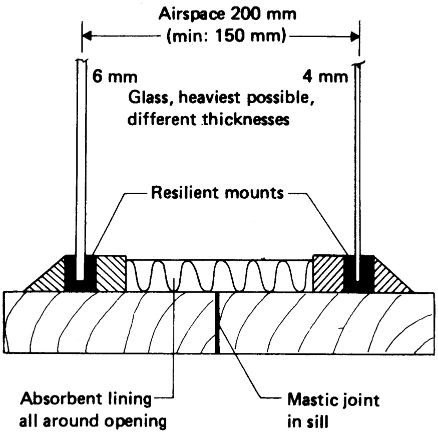


FIGURE 9.15 *Insulated double window*

Calculation of sound insulation

The sound reduction index used to measure the airborne sound insulation of a partition depends upon the amount of sound energy transmitted across the partition, as shown in figure 9.8.

The proportion of energy transmitted through the partition is measured by the *transmission coefficient, T*, where

$$T = \frac{\text{transmitted sound energy}}{\text{incident sound energy}}$$

The *sound reduction index* is then defined by the formula

$$\boxed{\text{SRI} = 10 \log_{10} \left(\frac{1}{T}\right)}$$

UNIT: decibel (dB).

* * * * *

Worked example 9.1

At a certain frequency a wall transmits 1 per cent of the sound energy incident upon it. Calculate the sound reduction index of the wall at this frequency.

Using T = (transmitted sound/incident sound) = $\frac{1}{100}$ = 0.01

$$\text{SRI} = 10 \log (1/T)$$

$$= 10 \log \left(\frac{1}{0.01}\right) = 10 \log (100) = 10 \times 2$$

SRI = **20 dB**

* * * * *

Composite partitions

A window placed in a well-insulated wall can greatly reduce the overall sound insulation of the wall, as was discussed in the section on completeness. Because SRIs have been calculated using a logarithmic formula they cannot be simply averaged according to area. But the overall transmission coefficient can be calculated using the transmission coefficients and areas of the individual components, such as windows and doors.
Then

$$T_0 = \frac{(T_1 \times A_1) + (T_2 \times A_2) + (T_3 \times A_3)}{A_1 + A_2 + A_3}$$

where

T_0 = overall transmission coefficient

T_1 = transmission coefficient of one component

A_1 = area of that component etc.

The overall sound reduction index for the complete partition can then be calculated using the overall transmission coefficient.

* * * * *

Worked example 9.2

A wall of area 10 m^2 contains a window of area 2 m^2. The SRIs are: 50 dB for the brickwork and 18 dB for the window. Calculate the overall SRI for the wall.

Let *Brickwork*: T_1 = ?, A_1 = 10 – 2 = 8 m^2, SRI = 50 dB. *Window*: T_2 = ?, A_2 = 2 m^2, SRI = 18 dB.

Using SRI = 10 log (1/*T*)

$$50 = 10 \log \left(\frac{1}{T_1}\right) \quad \text{and} \quad 18 = 10 \log \left(\frac{1}{T_2}\right)$$

$$\log \frac{1}{T_1} = 5 \qquad \log \frac{1}{T_2} = 1.8$$

$$\frac{1}{T_1} = 10^5 \qquad \frac{1}{T_2} = 63.10$$

$$T_1 = 10^{-5} \qquad T_2 = 1.585 \times 10^{-2}$$

Using $T_0 = \dfrac{(T_1 \times A_1) + (T_2 \times A_2)}{A_1 + A_2}$

$$= \frac{(10^{-5} \times 8) + (1.585 \times 10^{-2} \times 2)}{8 + 2} = \frac{3.18 \times 10^{-2}}{10}$$

$$= 3.18 \times 10^{-3}$$

Using SRI = 10 log $(1/T_0)$

$$= 10 \log \left(\frac{1}{3.18 \times 10^{-3}}\right) = 10 \log 314.5 = 25$$

Overall SRI = **25 dB**

* * * * *

EXERCISES

1 Use the information given in table 9.2 to plot points on a graph of sound insulation index against surface mass. Draw a best-fit line through the points to show the mass law relationship. Explain why some of the structures do not follow the mass law.

2 When the SRIs are measured for a certain double glazing unit the results obtained are those shown in figure 9.9. Explain the reason for the dips in the insulation curve and outline techniques that would help to reduce these effects.

3 Use the information given in table 9.3 to draw an annotated section of any wall that is considered to give sufficient sound insulation between dwellings. Explain which features of this wall help to provide the insulation.

4 (a) 800 units of sound energy are incident upon a wall and 10 of these units are transmitted through the wall. Calculate the SRI of this wall.

(b) If a window has a SRI of 33 dB then calculate the transmission coefficient of this window.

5 An external brick cavity wall is to be 4 m long and 2.5 m high. The wall is to contain one window 1.2 m by 800 mm and one door 750 mm by 2m. The relevant sound reduction indexes are: brickwork 53 dB; window 25 dB; door 20 dB. Calculate the overall SRI of the completed partition.

ANSWERS

4 (a) 19 dB
(b) 5.012×10^{-4}

5 27.4 dB

10 Room Acoustics

The subject of room acoustics is concerned with the control of sound in an enclosed space. The general aim is to provide the best conditions for the production and the reception of desirable sounds. Noise control was treated separately in chapter 9 but the exclusion of unwanted noise is an important element of room acoustics. Similarly, the acoustic quality of sound in a room can affect the way that people judge noise level.

GENERAL PRINCIPLES

General requirements

The detailed acoustic requirements for a particular room depend upon the nature and the purpose of the space. The general requirements for good acoustics can be summarised as follows:

(1) an adequate level of sound evenly distributed to all listeners in the room;
(2) a rate of decay (reverberation time) suitable for the type of room;
(3) background noise and external noise reduced to acceptable levels;
(4) absence of echoes and similar acoustic defects.

Types of auditorium

An auditorium is a room, usually large, designed to be occupied by an audience. The acoustic design of auditoria is particularly important and detailed acoustic requirements vary with the purpose of the space, as outlined below.

Speech The overall requirement for the good reception of speech is that the speech is *intelligible*. This quality will depend upon the power and the clarity of the sounds. Examples of auditoria that are especially used for speech are conference halls, law courts, theatres, and lecture rooms.

Music There are many more acoustic requirements for music than for speech. Music consists of a wide range of sound levels and frequencies which must all be heard. In addition, some desirable qualities of music depend on the listener's judgement and taste. These qualities are difficult to define but terms that are used include fullness of tone, definition of sounds, blend of sounds and balance of sounds.

Examples of auditoria designed exclusively for music are concert halls, opera houses, recording studios and practice rooms.

Multi-purpose There are some conflicts between the ideal acoustic conditions for music and for speech. Compromises have to be made in the design of auditoria for more than one purpose and the relative importance of each activity decided upon. Churches, town halls, school halls, and some theatres are examples of multi-purpose auditoria.

Sound paths in rooms

The behaviour of sound inside an enclosed space can produce many effects, some of which have special terms. However, the basic mechanisms are the wave properties of reflection, absorption, transmission and diffraction – as explained for light. Reflection and absorption play the largest part in room accoustics, the final effect depending upon the particular size, shape and materials of the enclosure.

REFLECTION

Sound is reflected in the same way as light, provided that the reflecting object is larger than the wavelength of the sound concerned. The angle of reflection equals the angle of incidence of the wave, as shown in figure 5.10. Using this rule, straight lines representing 'sound rays' can be drawn on plans and used to predict some of the effects of reflection. The special case of rapid reflections or reverberation is treated in a later section.

Types of reflector

Acoustic reflectors can be used to distribute sound evenly in an enclosure and to increase the overall sound level by reinforcement of the sound waves. The effect of a single plane reflector set above the stage is shown in figure 10.1. Reflectors should be wide enough to reflect sound across the full width of the audience and the reflected sound must not be significantly delayed.

At curved surfaces the angle of reflection still equals the angle of incidence but the geometry gives varying effects. Figure 10.2 illustrates the main type of reflection. In general

CONCAVE surfaces tend to focus sound.
CONVEX surfaces tend to disperse sound.

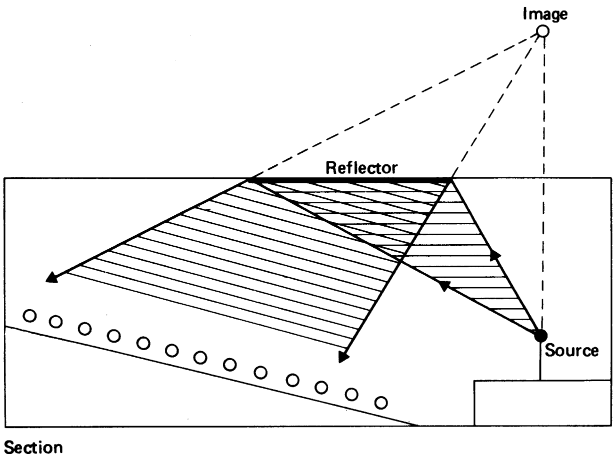


FIGURE 10.1 *Plane reflector of sound*

Convex surfaces can be useful for distributing sound but the concentration of sound provided by concave surfaces tends to be acoustically dangerous unless the focal point is well outside the enclosure. The domed ceilings of some public buildings, such as the Albert Hall, have often contributed to unsatisfactory acoustics.

Echoes

An echo is a *delayed reflection*. Initially a reflected sound reinforces the direct sound but if the reflection is delayed and is strong then this echo causes blurring

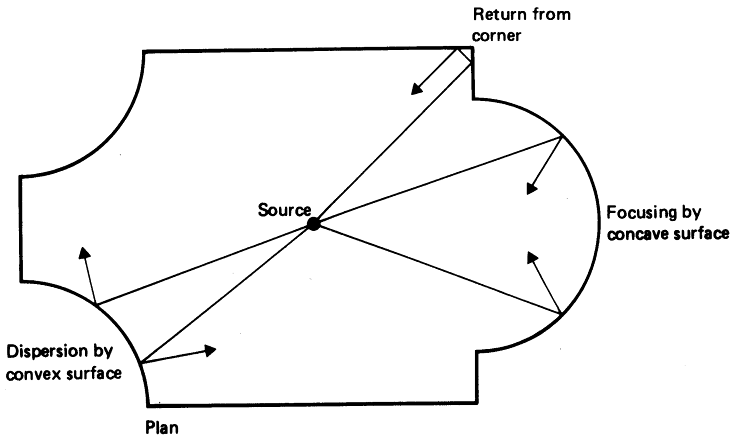


FIGURE 10.2 *Reflections from room surfaces*

and confusion of the original sound. The perception of echoes depends upon the power and the frequency of sounds.

There is a risk of a distinct echo if a strong reflection is received later than 1/20th second (50 ms) after the reception of the direct sound. At a velocity of 340 m/s this time difference corresponds to a path difference of 17 m. The difference in length between direct sound paths and reflected paths can be checked by geometry. Late reflections can be minimised by the use of absorbers on those surfaces that cause the echoes.

Flutter echoes are rapid reflections which cause a 'buzzing' quality as sound decays. They are caused by repeated reflections between smooth parallel surfaces, especially in smaller rooms. The flutter can be avoided by using dispersion and absorption at the surfaces.

Standing waves

Each frequency of a sound has a wavelength. Sometimes the distance between parallel walls in a room may equal the length of half a wave, or a multiple of a half wavelength. Repeated reflections between the surfaces cause standing waves or *room resonances*, which are detected as large variations in sound level at different positions. Standing wave effects are most noticeable for low-frequency sounds in smaller rooms and, in general, parallel reflecting surfaces should be avoided.

Hall shapes

Acoustic requirements are not the only factors deciding the internal shape of an auditorium. Good lines of sight from seats, for example, are a major requirement. The following aspects of internal design are likely to affect the acoustics of an auditorium.

A *rectangular plan* is the traditional shape of many successful concert halls. Reflectors can be used to direct sound to the rear of the hall and absorbers used to prevent unwanted reflections. Traditional ratios of dimensions for height, width and length are about 2 : 3 : 5.

A *fan shape* places the audience nearer the source of sound and can give them better views. A concave shape at the rear of the hall should be avoided.

A *horse-shoe shape* is common in traditional opera houses where the concave shape is broken up by tiers of seats and boxes. The audience in these tiers also acts as an absorber.

Raked seating prevents absorption of direct sound paths as well as reducing blocked views. Provision of good vision usually ensures a good sound path.

Figure 10.3 shows one possible plan and section for a concert hall which includes many of the features necessary for good acoustics.

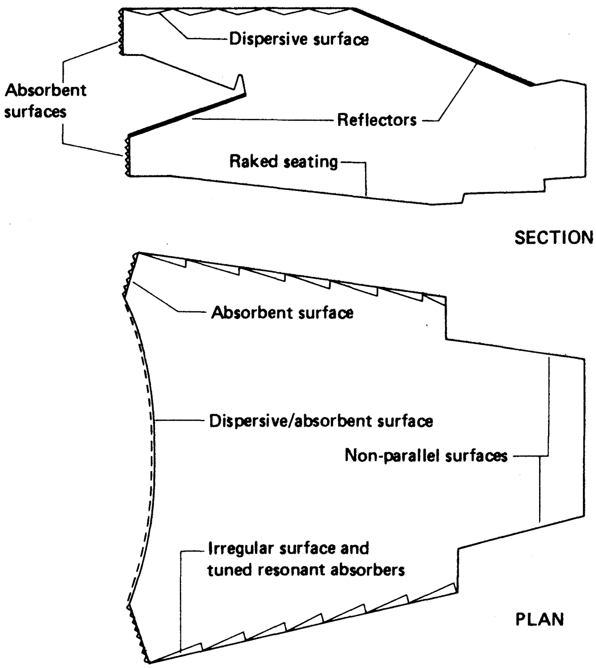


FIGURE 10.3 *Acoustic features of a concert hall*

ABSORPTION

Sound absorption is a reduction in the sound energy reflected from a surface. In chapter 9 sound absorption was distinguished from sound insulation – the two concepts have different effects and applications. Sound absorption is a major factor in producing good room acoustics, especially when controlling reverberation.

Absorption coefficient

The absorption coefficient is a measure of the amount of sound absorption provided by a particular type of surface. The amount of sound energy not reflected is compared with the amount of sound energy arriving at the surface in the following formula

$$\textbf{Absorption coefficient } (a) = \frac{\text{Absorbed sound energy}}{\text{Incident sound energy}}$$

UNIT: none – its value is expressed as a ratio.

Note that this coefficient of 'absorption' is a surface consideration and is not affected by what actually happens to the sound energy that is not reflected.

The perfect absorber has an absorption coefficient of 1.0 and an example of such an absorber is an open window. A surface that absorbs 40 per cent of incident sound energy has an absorption coefficient of 0.4. Different materials and constructions have different coefficients and the coefficient for any one material varies with the frequency of the incident sound. Table 10.1 lists the

TABLE 10.1 *Absorption coefficients*

Common building materials		Absorption coefficient		
		125 Hz	500 Hz	2000 Hz
Brickwork	plain	0.02	0.03	0.04
Clinker blocks	plain	0.02	0.06	0.05
Concrete	plain	0.02	0.02	0.05
Cork	tiles 19 mm, solid backing	0.02	0.05	0.10
Carpet	thick pile	0.10	0.50	0.60
Curtains	medium weight, folded	0.10	0.40	0.50
	medium weight, straight	0.05	0.10	0.20
Fibreboard	13 mm, solid backing	0.05	0.15	0.30
	13 mm, 25 mm airspace	0.30	0.35	0.30
Glass	4 mm, in window	0.30	0.10	0.07
	tiles, solid backing	0.01	0.01	0.02
Glass fibre	25 mm slab	0.10	0.50	0.70
Hardboard	on battens, 25 mm airspace	0.20	0.15	0.10
Plaster	lime or plaster, solid backing	0.02	0.02	0.04
	on laths/studs, airspace	0.30	0.10	0.04
Plaster tiles	unperforated, airspace	0.45	0.80	0.65
Polystyrene tiles	unperforated, airspace	0.05	0.40	0.20
Water	swimming pool	0.01	0.01	0.01
Wood blocks	solid floor	0.02	0.05	0.10
Wood boards	on joists/battens	0.15	0.10	0.10
Wood wool	25 mm slab, solid backing	0.10	0.40	0.60
	25 mm slab, airspace	0.10	0.60	0.60
Special items				
Air	per m^3			0.007
Audience	per person	0.21	0.46	0.51
Seats	empty fabric, per seat	0.12	0.28	0.28
	empty metal, canvas, per seat	0.07	0.15	0.18

average absorption coefficients of some common materials at the standard frequencies used in acoustic studies.

Total absorption

The effective absorption of a particular surface depends on the area as well as on the absorption coefficient of the material. A measure of this total absorption is obtained by multiplying the two factors together.

Absorption of a surface = Area of surface (m^2) x Absorption coefficient of that surface

UNITS: m^2 sabins or 'absorption units'.

The total absorption of a room is the sum of the absorptions provided by each surface in the room. It is the sum of the products of all areas and their respective absorption coefficients

Total Absorption = Σ (Area x Absorption coefficient)

People and soft furnishings absorb sound, and air also absorbs sound at higher frequencies. Absorption factors for these items are given in table 10.1.

Types of absorber

The materials and the devices used especially for the purpose of absorbing sound can be classified into three main types which have maximum effect at different frequencies, as indicated in figure 10.4:

(1) porous absorbers for high frequencies;
(2) panel absorbers for lower frequencies;
(3) cavity absorbers for specific lower frequencies.

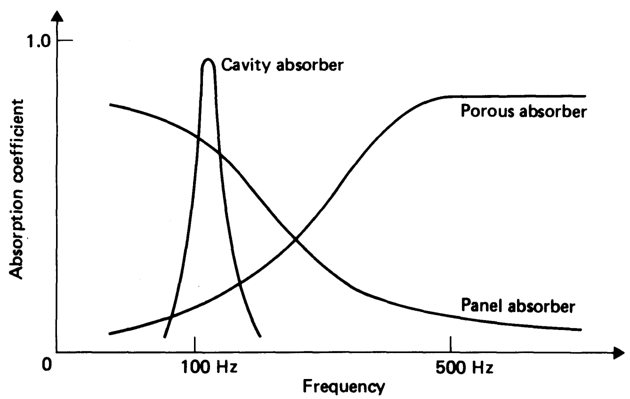


FIGURE 10.4 *Response of different absorbers*

Porous Absorbers Porous absorbers consist of cellular materials such as fibreglass and mineral wool. The air in the cells provides a viscous resistance to the sound waves which then lose energy as frictional heat. The cells should interconnect with one another and the closed cell structure of some foamed plastics is not always the most effective form for sound absorption.

Porous materials used for sound absorption include acoustic tiles, acoustic blankets and special coatings such as acoustic plaster. The absorption is most effective at frequencies above 1 kHz; the low frequency absorption can be improved slightly by using increased thickness of material.

Panel Absorbers Panel or *membrane* absorbers are fixed sheets of continuous materials with a space behind them; the space may be of air or may contain porous absorbent. The panels absorb the energy of sound waves by converting them to mechanical vibrations in the panel which in turn lose their energy as friction in the clamping system of the panel. The panels may be made of materials such as plywood or they may already exist, as for example in the form of windows or suspended ceilings.

The amount of absorption depends on the degree of damping in the system. The frequency at which maximum absorption occurs is the resonant frequency of the system, which depends on the mass of the panel and the depth of the airspace behind. This frequency is given by the formula

$$f = \frac{60}{\sqrt{(md)}}$$

where m and d are the measurements shown in figure 10.5.

This type of absorber is most effective for low frequencies in the range of about 40 to 400 Hz. A typical response curve is shown in figure 10.4.

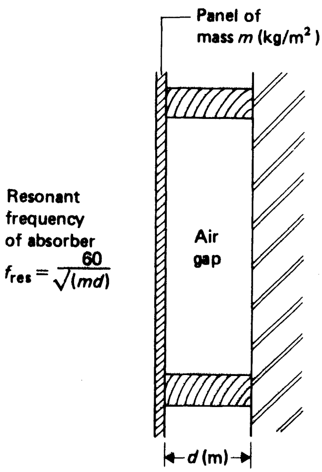


FIGURE 10.5 *Panel absorber*

Cavity Absorbers Cavity absorbers or *Helmholtz resonators* are enclosures of air with one narrow opening. The opening acts as an absorber when air in the opening is forced to vibrate and its viscous drag removes energy from the sound waves. In practice, the cavity may contain material other than air and be part of a continuous structure, such as in a perforated acoustic tile.

A cavity can provide a high absorption coefficient over a very narrow band of frequencies. The maximum absorption occurs at the resonant frequency of the cavity which is estimated by the formula:

$$f = 55\sqrt{\frac{a}{dV}}$$

where the measurements are shown in figure 10.6. The ability to tune a cavity absorber to specific frequencies is useful for controlling certain sounds inside rooms; a typical response curve is shown in figure 10.4.

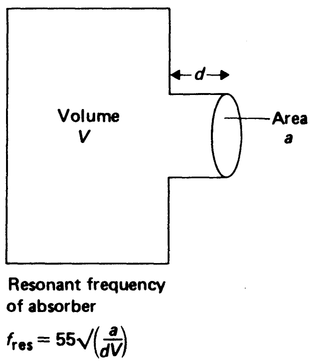


FIGURE 10.6 *Cavity absorber*

Practical absorbers

The acoustic tiles used on walls and ceilings often absorb sounds by several different methods, depending upon the frequency content of the sound. The basic material of the tile, such as fibreboard, is porous and acts as an absorbent for higher frequencies. The tile material may also be drilled with holes which then act as cavity absorbers.

Some tiles have a perforated covering, the holes in which form effective resonators. The tiles may also act as a panel absorber if they are mounted with an airspace behind them. In general, panel absorbers are used for low frequencies; perforated panels are used for frequencies in the range 200 to 2000 Hz, and porous absorbers are used for high frequencies.

REVERBERATION

If the only source of sound in a room suddenly stops, it is unlikely that a listener will hear the sound in the room also stopping suddenly. There will be a continuing presence of sound, known as reverberation, which is particularly noticeable in a building like a church.

> **REVERBERATION is the continuing presence of an audible sound after the source of the sound has been stopped.**

Reverberation is caused by rapid multiple reflections between the surfaces of a room. When a pulse of sound is generated in an enclosed space the listener first receives sound directly from the source. Following the direct sound the listener receives sound which has been reflected from the surfaces of the room; some simplified sound paths are shown in figure 10.7. As the number of reflections increases the distance travelled increases, and so the sound waves become later and weaker.

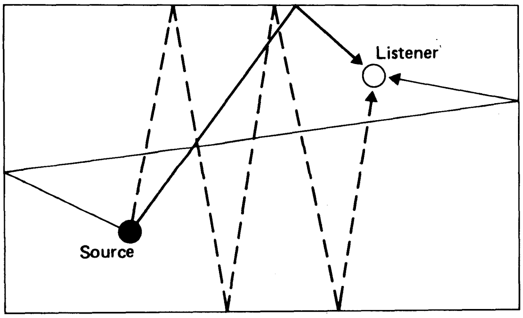


FIGURE 10.7 *Multiple reflections of reverberation*

The multiple reflections reach the listener too rapidly for them to be heard as separate sounds or echoes and so the reverberations are heard as an extension of the original sound. If the original source of sound is a continuous one then the reverberant sound combines with the direct sound to produce a reverberant sound level.

Reverberation time

The sound waves that cause reverberation lose intensity as they are absorbed at each reflection and if the source of sound stops then the reverberant sound level decays, as shown in figure 10.8. In order to specify this quality of the

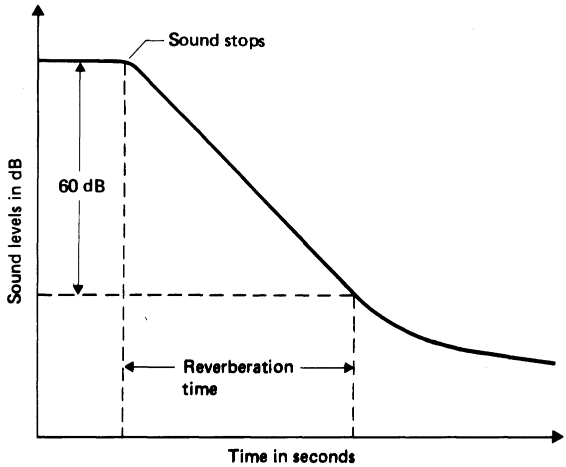


FIGURE 10.8 *Reverberation time*

reverberation, the rate at which the decay occurs can be measured by the reverberation time.

REVERBERATION TIME is the time taken for a sound to decay by 60 dB from its original level.

A decrease in sound level of 60 dB, which is the same as a drop to one millionth of the original sound power, represents the decay of a moderately loud sound to inaudibility. The time taken for this decay in a room depends upon the following factors:

1. the distances between the surfaces of the room;
2. the absorption at the surfaces;
3. the frequency of the sound.

The reverberation time of an enclosure is an important index for describing and for comparing its acoustical quality. The time can be directly measured in a room, or it can be calculated from a knowledge of the factors that affect reverberation time.

Ideal reverberation time

Typical reverberation times vary from a fraction of a second in small rooms to 5 s and more in very large enclosures like a cathedral. Different types of room and activities require different reverberation times for acceptable acoustical quality.

In general, the best reverberation times are less than 1 s for speech and longer than 1 s for music. Short reverberation times are necessary for clarity of speech, otherwise the continuing presence of reverberant sound will mask the next sound and cause the speech to be blurred. Longer reverberation times are considered to enhance the quality of music which will sound 'dry' or 'dead' if the reverberation time is too short.

Larger rooms are judged to require longer reverberation times, as is also the case with lower frequencies of sound. Exact values can be calculated by a formula such as the *Stephens and Bate* formula:

$$t = r[0.0118\sqrt[3]{(V + 0.107)}]$$

where

t = reverberation time in s

V = volume of hall in m^3

r = 4 for speech, 5 for orchestras, 6 for choirs

Ideal reverberation times can also be presented in sets of graphs, such as those shown in figure 10.9.

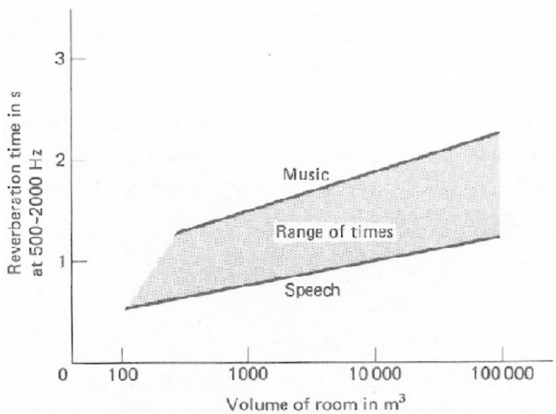


FIGURE 10.9 *Optimum reverberation times*

Formulas for reverberation time

When reverberation time cannot be directly measured, as at the planning stage for example, it can be predicted from a knowledge of the factors that affect the decay of sound. Reverberation time depends on the volume of an enclosure, on the total surface area and the absorption coefficients of the surfaces. If these factors are numerically related by a formula then one of the factors can be calculated if the others are known.

Sabine's Formula Sabine's formula assumes that the reverberant decay is continuous and it is found to give reasonable predictions of reverberation time for rooms without excessive absorption

$$\boxed{t = \frac{0.16V}{A}}$$

where

t = reverberation time (s)

V = volume of the room (m^3)

A = total absorption of room surfaces (m^2 sabins)

$= \Sigma$ (area x absorption coeff.)

Eyring Formula If the average absorption in a room is high, such as in a broadcasting studio, the reverberation times predicted by Sabine's formula do not agree with actual results. A more accurate prediction is given by the Eyring formula.

$$t = \frac{0.16V}{-S \log_e(1 - \bar{a})}$$

where

t = reverberation time (s)

V = volume of the room (m^2)

S = total area of surfaces (m)

$\bar{a}$ = average absorption coeff. of the surfaces

Calculation of reverberation time

Reverberation times are calculated by finding the total absorption units in a room and then using a formula such as Sabine's formula. The absorption of materials varies with frequency and the reverberation time predicted by formula is only accurate for the frequency at which absorption coefficients are valid.

If the same value of reverberation time is required at different frequencies then the average absorption must be the same at each frequency. This can be achieved by choosing materials or devices that provide absorption at certain frequencies and not at others.

The worked examples illustrate common types of calculation and the following points should be noted:

(1) Reverberation times cannot be directly added or subtracted with one another – adjustments must be made by addition or subtraction of absorption units.
(2) A sketch of the enclosure with dimensions will help in accurately identifying all surfaces and their areas.
(3) Surfaces that are not seen do not usually provide absorption – for example, floor covered by carpet.
(4) It is advisable to tabulate all surfaces with their respective areas and absorptions, as shown in worked example 10.2, below.

* * * * *

Worked example 10.1

A hall has a volume of 5000 m^3 and a reverberation time of 1.6 s. Calculate the amount of extra absorption required to obtain a reverberation time of 1 s.

$t_1 = 1.6$ s, $A_1 = ?$ $V = 5000$ m^3, $t_2 = 1.0$ s, $A_2 = ?$

Using $t = 0.16V/A$

$$\text{for } t_1 : 1.6 = \frac{0.16 \times 5000}{A_1}; \quad A_1 = \frac{0.16 \times 5000}{1.6} = 500 \text{ sabins}$$

$$\text{for } t_2 : 1.0 = \frac{0.16 \times 5000}{A_2}; \quad A_2 = \frac{0.16 \times 5000}{1.0} = 800 \text{ sabins}$$

Extra absorption needed $= A_2 - A_1 = 800 - 500$

$= \mathbf{300\ m^2\ sabins}$

Worked example 10.2

A lecture hall with a volume of 1500 m^3 has the following surface areas and finishes and absorption coefficients (500 Hz)

Walls, plaster on brick	400 m^2 (0.02)
Floors, plastics tiles	300 m^2 (0.05)
Ceiling, plasterboard on battens	300 m^2 (0.10)

Calculate the reverberation time at 500 Hz of this hall when it is occupied by 100 people.

Tabulate information and calculate absorption units using:

Absorption = Area x Absorption coefficient

		500 Hz	
Surface	Area	Absorption coefficient	Abs. units (m^2 sabins)
Walls	400 m^2	0.02	8
Ceiling	300 m^2	0.10	30
Floor	300 m^2	0.05	15
Occupants	100 people	0.46 each	46
		Total A	99 sabins

Using Sabine's formula

$$t = \frac{0.16V}{A} = \frac{0.16 \times 1500}{99} = 2.42$$

Reverberation time = **2.42** s at 500 Hz

Worked example 10.3

The reverberation time required for the hall in worked example 10.2 is 0.8 s. Calculate the area of acoustic tiling needed on the walls to achieve this reverberation time (absorption coefficient of tiles = 0.4 at 500 Hz).

The areas of tiles will change the original area of plain walls. The areas can be found by trial and error, or by algebra as shown

		500 Hz	
Surface	Area m^2	Absorption coefficient	Abs. units (m^2 sabins)
Tiles	S	0.40	$0.4S$
Walls	$400 - S$	0.02	$8 - 0.02S$
Ceiling	300	0.10	30
Floor	300	0.05	15
Occupants	100 people	0.46 each	46
		Total $A = 99 + 0.38S$	

Using $t = \dfrac{0.16V}{A}$

$$0.8 = \frac{0.16 \times 1500}{99 + 0.38S}$$

$$3.8S = \frac{0.16 \times 1500}{0.8} - 99 = 300 - 99 = 201$$

$$S = \frac{201}{3.8} = 52.9$$

Area of tiles = **52.9 m²**

*   *   *   *   *

EXERCISES

1 Draw a plan and a section of a hall similar to that in figure 10.3, or one of your own choosing. For a sound source situated on the centre of the stage, draw sound ray diagrams to show the distribution of sound by reflections off the ceiling and the walls.

2 A room of 900 m^3 volume has a reverberation time of 1.2 s. Calculate the amount of extra absorption required to reduce the reverberation time to 0.8 s.

3 Calculate the actual reverberation time for a hall with a volume of 5000 m^3, given the following data for a frequency of 500 Hz

Surface area	Absorption coefficient
500 m^2 brickwork	0.03
600 m^2 plaster on solid	0.02
100 m^2 acoustic board	0.70
300 m^2 carpet	0.30
70 m^2 curtain	0.40
400 seats	0.30 units each

4 If the optimum reverberation time for the above hall is 1.5 s then calculate the number of extra absorption units needed.

5 A large cathedral has a volume of 120 000 m^3. When empty the reverberation time is 9 s. With a certain congregation the reverberation time is reduced to 6 s. Calculate the number of people present, if each person provides an absorption of 0.46 m^2 sabins.

6 A rectangular hall has floor dimensions 30 m by 10 m and a height of 5 m. The total area of windows is 50 m^2. The walls are plaster on brick, the

ceiling is hardboard on battens and the floor is wood blocks on concrete. There are 200 fabric seats. The reverberation time required for the hall, without audience, is 1.5 s at 500 Hz. Use table 10.1 to help calculate the area of carpet needed to achieve the correct reverberation time.

ANSWERS

2. 60 sabins
3. 2.4 seconds
4. 198.3 sabins
5. 2319 people
6. 71.1 m^2 carpet

11 Electricity

A supply of electricity is essential for creating and controlling the environment in a modern building. Heating, cooling, ventilating and lighting systems use electricity; for its energy content and for the ease with which it can be controlled. Electricity also provides the large amounts of energy needed for pumping public water supplies.

This chapter explains the basic principles of electric currents and electric devices, such as generators and motors. These principles are then used to describe modern systems of generating and distributing electricity.

CURRENT ELECTRICITY

Structure of matter

All material is made of atoms. An *atom* is the smallest part of matter that has a separate chemical existence. Atoms contain many smaller particles and among the forces that bind the sub-atomic particles together is an electric property called charge. There are two kinds of charges: positive (+) and negative (–). The forces between charges obey the following rules

Like charges repel one another.
Unlike charges attract one another.

There are three fundamental sub-atomic particles which decide the nature of matter and give rise to electrical effects. The important properties of the fundamental sub-atomic particles are shown in figure 11.1 and summarised below:

Protons:
(a) have a positive electric charge, equal and opposite to that of the electron;
(b) have a mass of 1 atomic mass unit;
(c) are found in the central nucleus.

Neutrons:
(a) have no electric charge so are 'neutral';
(b) have the same mass as the proton;
(c) are found in the nucleus with the proton.

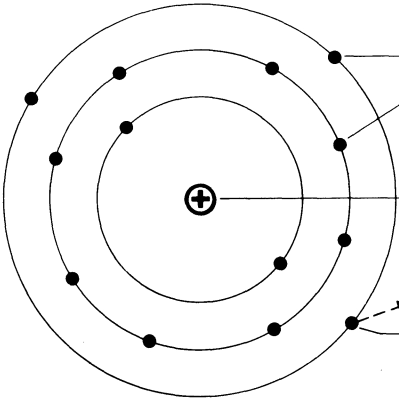


FIGURE 11.1 *Aluminium atom, simple model*

Electrons:

(a) have a negative electric charge, equal and opposite to that of the proton;
(b) have very small mass, approximately 1/1840 atomic mass unit;
(c) are found surrounding the nucleus.

The nucleus occupies a very small volume at the centre of the atom but contains all the protons and neutrons. Therefore, despite its small size, the nucleus contains nearly all the mass of an atom. The electrons can be considered as circulating in orbits around the nucleus, held in position by the opposing charge of the protons in the nucleus. An atom contains the same number of electrons as protons, so the positive and negative charges are balanced and the overall charge of an atom is zero.

The electrons in the outer orbits are held by relatively weak forces so outer orbits can sometimes lose or gain electrons. *Free electrons* are electrons in outer orbits that are able to move from one atom to another. Ionisation is a process in which an atom permanently gains or loses electrons and so acquires an overall charge. This charged atom is then called an *ion*.

Whatever the mechanism, when electrons move from one place to another they transfer their electric charge. It is this charge that electricity is composed of.

CHARGE (Q) is the basic quantity of electricity.

UNIT: coulomb (C).

The idea of charge or static electricity is more fundamental than current electricity. Although current electricity is more usual in everyday applications, electricity does not have to move to exist. A thundercloud, for example, contains a huge quantity of electricity, which does not flow, except during a stroke of lightning.

Electric current

If electric charge transfers through a material then an electric current is said to flow. The movement of free electrons is the usual mechanism for the transfer of charge. The amount of electric current is described by the speed at which charge passes a fixed point.

ELECTRIC CURRENT (I) is the rate of flow of charge in a material.

UNIT: ampere (A).

So that $$I = \frac{Q}{t}$$

where

I = electric current flowing (A)

Q = electric charge (C)

t = time taken (s)

Direction of Current Electrons have a negative charge and, by the rules of charge, they are attracted to a positive charge. Therefore when electrons move through a material, such as a cable, they are attracted to the positive side of the electrical supply, as shown in figure 11.2. However, by convention, it is usual to say that direct electric current flows from positive to negative, even though this is the opposite direction to the electron flow. This convention works for practical problem solving as long as it is maintained consistently.

Effects of Current Electrons are too small to be detected themselves, but the

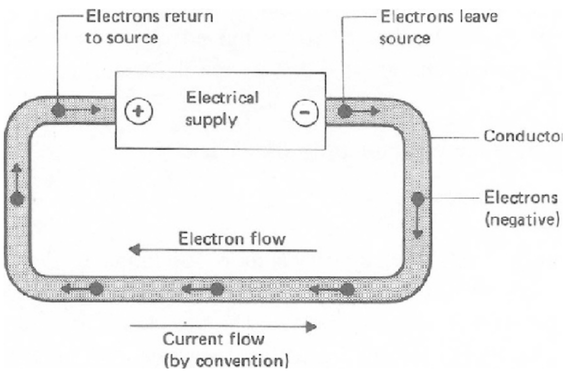


FIGURE 11.2 *Electron and current flow*

presence of an electric current can be known by its effects. Three important effects are listed below:

(1) *Heating effect* Current flowing in a conductor generates heat. The amount of heat depends upon the amount of current but not on its direction. The heating effect is made use of in electric heaters and fuses, for example.
(2) *Magnetic effect* Current flowing in a conductor produces a magnetic field. The size and direction of the field is affected by the size and direction of the current. This effect is used in electric motors, for example.
(3) *Chemical effect* Current flowing through some substances causes a chemical change and produces new substances. The type of change depends upon the amount and direction of the current. This type of effect is used in electroplating and refining, for example.

Conductors and insulators

If a material allows a significant flow of electric current then the material is said to be a conductor of electricity. A material that passes relatively little current is said to be an insulator.

Conductors Solid conductors are materials whose free electrons readily produce a flow of charge. If the conductor is a liquid or a gas then the charge is usually transferred by the movements of ions. Common types of conductor are listed below:

1. *Metals* Examples: copper and aluminium cable conductors.
2. *Carbon* Example: sliding contacts in electric motors.
3. *Liquids and gases which have been ionised* Example: gas discharge lamps.

Insulators Insulators are materials that have few free electrons available to produce a flow of charge. Common types of insulator are listed below:

1. *Rubber and plastic polymers* Example: PVC cable insulation.
2. *Mineral powder* Example: magnesium oxide cable insulation (MICC).
3. *Oil* Example: underground cable insulation.
4. *Dry air* Example: overhead power line insulation.
5. *Porcelain and glass* Example: overhead power line insulation.

Electrical pressure

Potential Difference For an electric current to flow in a conductor there must be a difference in charge between two points. This potential difference is similar to the pressure difference that must exist for water to flow in a pipe.

POTENTIAL DIFFERENCE (pd or *V*) is a measure of the difference in charge between two points in a conductor.

UNIT: volt (*V*).

The volt is defined in terms of the energy needed to move an electric charge. Because potential difference is measured in volts it is sometimes termed 'voltage drop'. Current flows from the point of higher potential to the point of lower potential, as shown in figure 11.3.

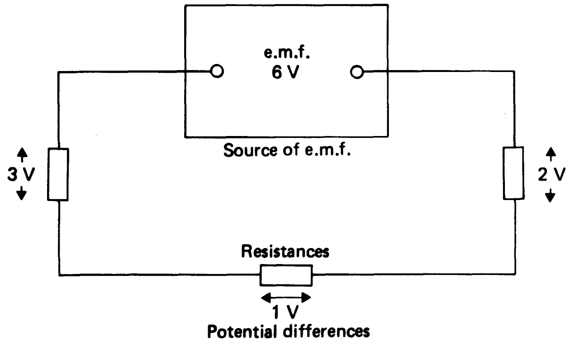


FIGURE 11.3 *Potential difference and electromotive force*

Electromotive Force In order to produce a potential difference and the resulting current, there must be a source of electrical 'pressure' acting on the charge. This source, shown in figure 11.3, is called an electromotive force (e.m.f.).

An ELECTROMOTIVE FORCE (*E*) is a supply of energy capable of causing an electric current to flow.

UNIT: volt (V).

Because the unit of e.m.f. is the volt, the same unit as for potential difference, the e.m.f. of a circuit is sometimes called the 'voltage'. Common sources of e.m.f. are batteries and generators.

Resistance

Some materials oppose the flow of electric current more than others. Resistance is a measure of opposition to the flow of electric current and is related to the potential difference and the current associated with that opposition.

$$\textbf{RESISTANCE } (R) = \frac{\text{Potential difference } (V)}{\text{Current } (I)}$$

UNIT: ohm (Ω), where 1 Ω = 1 V/A.

A resistor is a component that is used to provide resistance and its resistance depends upon the following factors:

1. *Length* Doubling the length doubles the resistance.
2. *Cross-sectional area* Doubling the area halves the resistance.
3. *Temperature* The resistance of most metals increases with temperature.
4. *Material* The resistance provided by a particular material is given by a value of *electrical resistivity*. The resistivity of copper, for example, is about $\frac{1}{2}$ that of aluminium, about $\frac{1}{6}$ that of iron, and about 10^{-20} that of a typical plastic.

Ohm's Law The potential difference and the current associated with a resistance may be measured and the values compared. For most metal conductors it is found that if, for example, the potential difference is doubled then the current also doubles. This relationship is expressed as Ohm's Law.

For a metal conductor, at constant temperature, the current flowing is directly proportional to the potential difference across the conductor.

The constant of proportionality is, by definition, the resistance of the conductor; so that a useful expression resulting from Ohm's Law is

$$\boxed{V = IR}$$

where

V = potential difference across a component (V)

I = current flowing in the component (A)

R = resistance of the component (Ω)

Note that this expression can also be expressed in two other forms

$$I = \frac{V}{R} \quad \text{and} \quad R = \frac{V}{I}$$

* * * * *

Worked example 11.1

An electronic calculator has an overall resistance of 6 kΩ and is connected to a supply which provides a potential difference of 9 V. Calculate the current flowing to the calculator.

$V = 9$ V $\qquad I = ?$ $\qquad R = 6000\ \Omega$

Using

$$V = IR$$

$$9 = I \times 6000$$

$$I = \frac{9}{6000} = 1.5 \times 10^{-3}\ \text{A}$$

current = **1.5 mA**

*   *   *   *   *

Circuits

For a continuous electric current to be able to flow there must be a complete circuit path from, and back to, the source of electromotive force. In most circuits this complete path is supplied by two obvious conductors connecting the electrical device to the supply. Some systems, however, use less obvious means, such as the conduction of a metal structure or of the earth itself as one part of the circuit. For example, the metal chassis of a car or a television set is part of the circuit; and the earth itself forms part of the circuit for the distribution of electrical energy.

For simple problems the resistance of the connecting conductors is assumed to be negligible. The voltage drop produced by the resistance of practical lengths of cable can be predicted from published tables and, if it is excessive, a cable of lower resistance is used. The theoretical layout of circuits is shown in a geometrical manner using standard symbols, as used for the diagrams in this chapter. In an actual wiring system the connections are made on the components, rather than on the conductors as shown in the circuit diagrams.

Circuit rules

There are certain basic principles regarding the behaviour of current, voltage and resistance that apply to any circuit or part of a circuit. If some of the electrical values are known for a circuit then others can be predicted by the use of these rules.

There are two basic layouts for connecting components in a circuit: parallel and series connection. Figures 11.4 and 11.5 show the two types of circuit using three components, but the circuit rules apply to any number of components.

Series Connection

1. *Current* The current flowing in each resistor has the same value.
2. *Voltage* The sum of the voltage drops across all the resistors is equal to the applied voltage

$$V = V_1 + V_2 + V_3$$

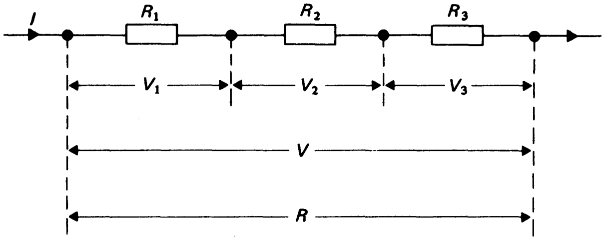


FIGURE 11.4 *Resistors connected in series*

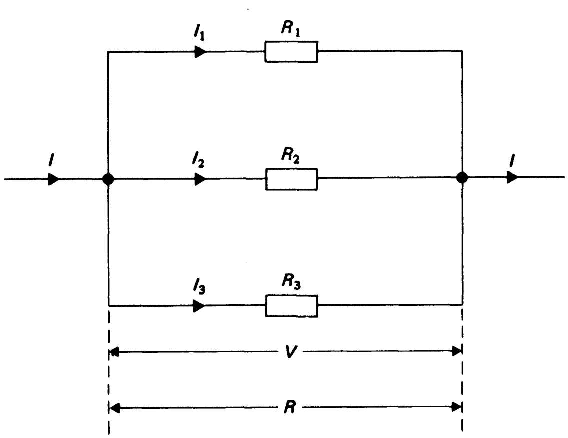


FIGURE 11.5 *Resistors connected in parallel*

3. *Resistance* The total resistance of the circuit is equal to the sum of the individual resistances

$$R = R_1 + R_2 + R_3$$

Parallel Connection

1. *Current* The sum of the currents in all the resistors is equal to the total current flowing in the circuit

$$I = I_1 + I_2 + I_3$$

2. *Voltage* The voltage drop (pd) across each resistor has the same value.
3. *Resistance* The total resistance of the circuit is obtained from the reciprocals of the individual resistances

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

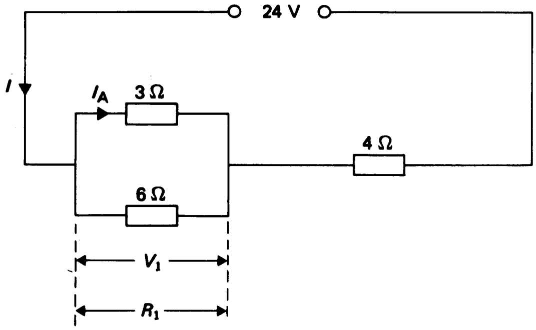


FIGURE 11.6 *Worked example 11.2*

* * * * *

Worked example 11.2

A 3 Ω and a 6 Ω resistor are connected together in parallel and then connected in series with a 4 Ω resistor. If an e.m.f. of 24 V is applied to this circuit then calculate the following:

(a) The total resistance of the circuit.
(b) The total current flowing in the circuit.
(c) The potential difference across the 3 Ω resistor.
(d) The current flowing in the 3 Ω resistor.

Draw the circuit and label the known and unknown values, as in figure 11.6.

(a) Total resistance R

$$\frac{1}{R_1} = \frac{1}{3} + \frac{1}{6} = \frac{2+1}{6} = \frac{3}{6}, \quad R_1 = 2\ \Omega$$

$$R_2 = 4\ \Omega$$

$$R = R_1 + R_2 = 2 + 4 = \mathbf{6\ \Omega}$$

(b) Total current I

Total R = 6 Ω, Total V = 24 V

$$I = \frac{V}{R} = \frac{24}{6} = \mathbf{4\ A}$$

(c) Potential difference V_1

Resistance R_1 = 2 Ω, current in R_1 = 4 A

$$V_1 = I \times R_1 = 4 \times 2 = \mathbf{8\ V}$$

(d) Current I_A:

$$I_A = \frac{V_1}{R} = \frac{8}{3} = 2.67 \text{ A}$$

* * * * *

Cells

A cell is a device that converts chemical energy to electrical energy and supplies an electromotive force capable of causing a direct electric current to flow. There are two classes of cell: primary and secondary cells.

Primary cells are cells that can *not* be recharged. The conversion of energy is not reversible and the cell must be replaced. Examples of these cells would be simple cells, zinc–carbon cells, dry mercury cells, alkaline manganese cells and silver oxide cells.

Secondary cells are cells that can be recharged. The conversion process can be reversed, the energy content replaced, and the cell can be used again. Examples of these cells would be lead–acid accumulators and nickel–cadmium cells.

Most cells have the same basic components and some common types of cell are described below. The *electrodes* are conductors which form the terminals of the cell, the *anode* is the positive electrode and the *cathode* is the negative electrode. The *electrolyte* is a compound that undergoes chemical change and releases energy.

Simple Cell A simple or 'voltaic' cell is a primary cell which is constructed as shown in figure 11.7. This cell is not a practical source of supply as it has a

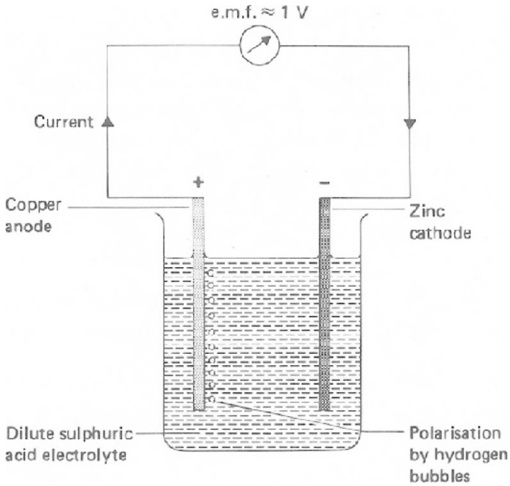


FIGURE 11.7 *Simple cell*

limited life, mainly because of polarisation. *Polarisation* is a reverse e.m.f. set up in the cell because hydrogen is liberated and deposited on the copper electrode. The general nature of a simple cell is an important mechanism in *electrolytic corrosion* when simple cells can occur between neighbouring areas of different metals.

Dry Cell The dry cell or zinc–carbon cell is the commonest type of primary cell and its construction is shown in figure 11.8. The dry cell is a form of *Leclanché cell* with the electrolyte made as a paste rather than a liquid. The nominal e.m.f. of any single dry cell is 1.5 V and the cell contains a depolarising agent. It is suitable for intermittent use in torches, radios and similar devices.

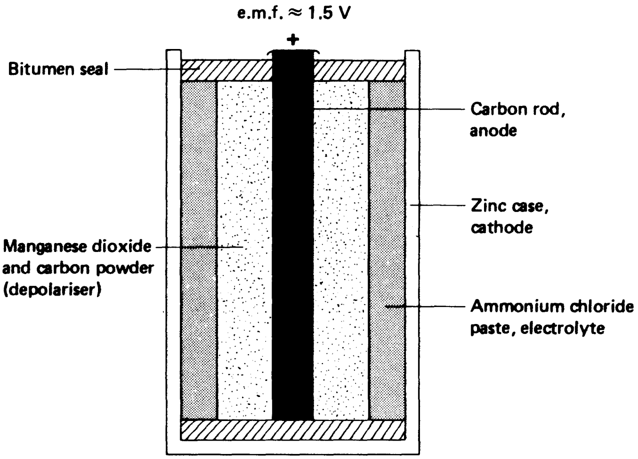


FIGURE 11.8 *Dry cell*

Lead–Acid Cells The lead–acid cell is the commonest type of secondary cell and is used in most motor vehicles. The electrodes are made of lead and lead oxide set in lead alloy grids; the electrolyte is dilute sulphuric acid. Each electrode changes from one form of lead to the other as the cell is charged or discharged; the concentration of the acid electrolyte indicates the state of charge. The e.m.f. of any single lead–acid cell is 2 V.

Connections Between Cells A *battery* is a combination of more than one cell connected together to give an increased e.m.f. or increased capacity:

Series connection This type of connection is shown in figure 11.9. The total e.m.f. of the battery is the sum of the individual e.m.f.s.

Parallel connection This type of connection is shown in figure 11.10. The total e.m.f. of the battery is equal to the e.m.f. of a single cell. The maximum current or the life of the battery is three times that of a single cell.

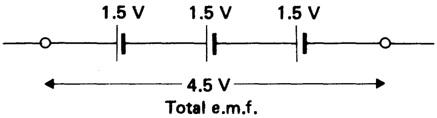


FIGURE 11.9 *Cells connected in series*

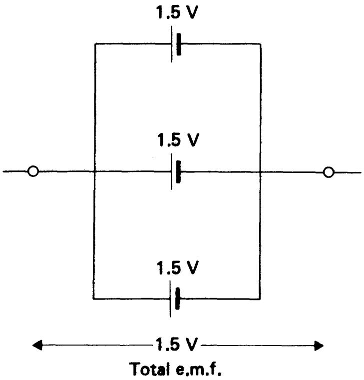


FIGURE 11.10 *Cells connected in parallel*

Power and energy

Electrical energy and power have the same meaning and the same units as other forms of power and energy. Power is the rate of using energy and, because the volt is defined in terms of electric charge and energy, it is possible to express power in terms of electric current (flow of charge) and voltage.

POWER (P) = Current (I) x Potential difference (V)

$$\boxed{P = IV}$$

UNIT: watt (W) where, by definition, 1 watt = 1 joule/second.

By combining the expressions $P = IV$ and $V = IR$, two other useful expressions are produced

$$P = I^2R \quad \text{and} \quad P = \frac{V^2}{R}$$

The *power rating* of an electrical appliance is often quoted in specifications and it is an indication of the relative energy consumption of the device.

Some typical power ratings are:

electric kettle element – 2500 W;
electric fire (1 bar) – 1000 W;
colour television – 100 W;
reading lamp – 60 W;
calculator charger – 5 W.

Power is defined by the energy used in a certain time, so it is possible to express energy in terms of power and time.

ENERGY (E) = Power (P) x Time (t)

$$\boxed{E = Pt}$$

UNIT: joule (J) where 1 joule = 1 watt x 1 second. Another unit of energy in common use for electrical purposes is kilowatt hour (kWh) where 1 kWh = 1 kilowatt x 1 hour = 3.6 MJ.

* * * * *

Worked example 11.3

A 3 kWh electric heater is connected to a 240 V supply and run continuously for 8 hours. Calculate: (a) the current flowing in the heater; and (b) the total energy used by the heater.

(a) $P = 3000$ W, $I = ?$, $V = 240$ V.

Using $P = IV$

$$3000 = I \times 240$$

$$I = \frac{3000}{240} = 12.5$$

Current = **12.5 A**

(b) $E = ?$, $P = 3$ kW $= 3000$ W, $t = 8$ h $= 28\,800$ s.

Using

$$E = Pt$$

$$E = 3000 \times 28\,800 = 86.4 \times 10^6 \text{ J}$$

or

$$E = 3 \times 8 = 24 \text{ kWh}$$

Energy = **86.4 MJ** or **24 kWh**

* * * * *

MAGNETISM

There are certain pieces of iron, and other materials, that can push or pull on one another when there is no contact between them. This force of magnetic attraction or repulsion is caused by the movement of charged particles inside the material. This motion may be due to the natural spin of sub-atomic particles, like the electron, or it may be due to the flow of electrons in an electric current. Magnetism is therefore linked with electric currents. This section describes those effects where electricity and magnetism combine to produce forces which can be used in devices such as motors.

Magnetic fields

The individual atoms of all materials have magnetic properties but they are not usually detected outside the atoms. In certain materials the magnetic effects of the individual atoms can be aligned to produce an overall effect. Iron, nickel and cobalt, for example, can retain this magnetic alignment and are used to make permanent magnets.

A *magnetic field* is a region where a magnetic force can be detected. The common sources of magnetic fields include:

1. permanent magnetic materials, such as iron;
2. a conductor carrying an electric current;
3. the interior of some planets, such as Earth.

A simple *compass* is made from a magnet balanced on a string or a pivot. In the presence of a magnetic field the compass will turn and align itself in the direction of the magnetic field. The direction of the magnetic field changes with position and it is useful to consider this pattern of the magnetic field as being made up of 'lines of force' or *magnetic flux*.

The magnetic field pattern for a simple bar magnet, in one plane only, is shown in figure 11.11. The lines of magnetic flux begin and terminate at the two

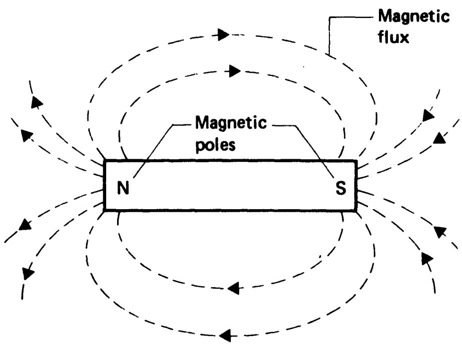


FIGURE 11.11 *Magnetic field of bar magnet*

poles of the magnet: a 'north-seeking pole' and a 'south-seeking pole'. By convention, the magnetic field is said to flow from north pole to south pole.

When two magnets are placed close together the forces between them act towards or away from the poles of the magnets. The direction of the force follows the general rule

Unlike poles attract one another.
Like poles repel one another.

Two north poles, for example, will push away from one another; while a north and a south pole pull towards one another.

Electromagnetism

A conductor carrying an electric current produces a magnetic field around itself. A compass placed near a wire shows that the field is in the form of concentric circles; in a clockwise direction for current travelling away from view. A single turn of a loop of wire sets up two magnetic fields which combine, in the same direction, between the loops.

A *solenoid* is coil made up of many loops of wire. When a current flows in a solenoid the magnetic field produced around the solenoid, shown in figure 11.12, is found to be similar to that of a bar magnet, with north and south poles produced at the ends of the solenoid.

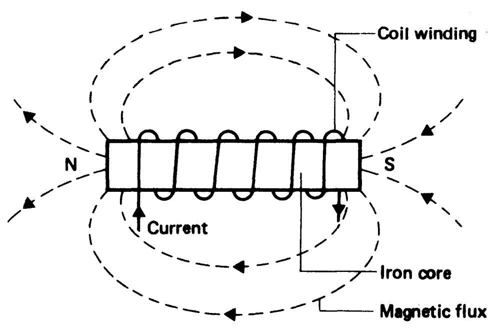


FIGURE 11.12 *Magnetic field of solenoid*

An *electromagnet* is the general name given to a solenoid that is connected to an electric supply. If the solenoid is wound on a *core* of iron the lines of magnetic flux are concentrated and change the shape of magnetic field.

Applications of electromagnets

The main property of an electromagnet is its dependence on the supply of current: it can be turned on and off. Electromagnets are used instead of permanent magnets as a source of magnetic fields. Some important applications of electromagnets are given below:

1. lifting iron and steel, such as in scrap metal yards;
2. solenoid valves for turning supplies of gas and water on;
3. electric bells and buzzers;
4. relay switches for controlling circuits at a distance;
5. circuit breakers for preventing excessive current flows.

Electric Bell An electric bell or buzzer uses an electromagnet as shown in figure 11.13. Pressing the bell-push connects the bell to the supply and magnetises the electromagnet which then attracts the armature – but the movement of the armature breaks the circuit at the contact points and the magnetism dies away. The armature springs back to its original position, completes the circuit and starts the cycle again. The continuous trembling of the armature can be used to ring a bell, or to produce a buzzing sound, for as long as the switch is pushed.

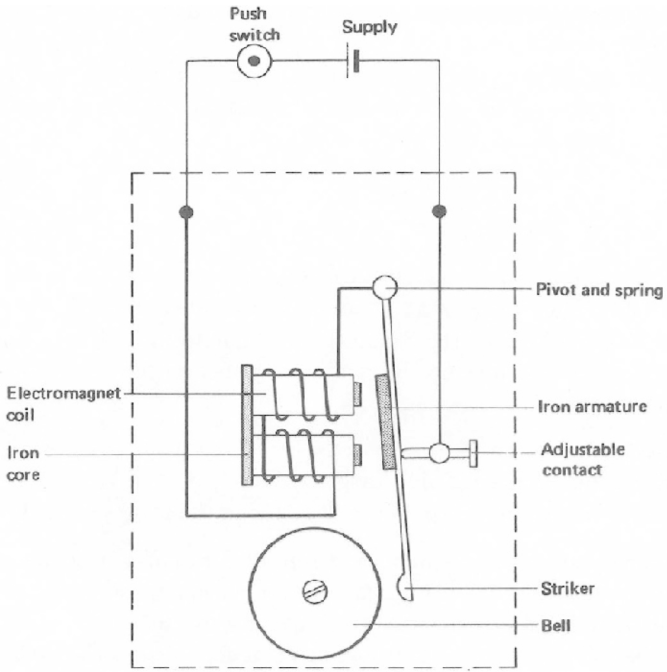


FIGURE 11.13 *Electric bell*

Relay A relay switch is a device used for controlling one circuit by means of another circuit. A relay uses the force produced by an electromagnet and a simple example is shown in figure 11.14. Switching on the control circuit magnetises the electromagnet which then attracts the armature. The movement

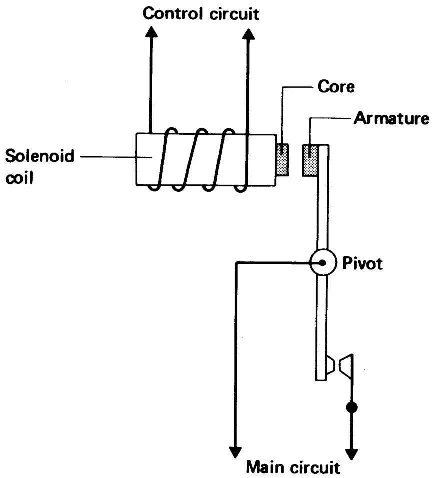


FIGURE 11.14 *Principle of relay switch*

of the armature closes the contacts of the relay switch and causes the main circuit to be turned on.

The advantage of this type of switch is that the control circuit can use low voltage and current to control a main circuit which carries a larger load and is situated some distance away.

Force on a conductor

When a conductor in a magnetic field carries a current, a force is found to act on that conductor. This *motor effect* is caused by the interaction of two magnetic fields: the field due to the magnet and the field due to the current.

The strength of the force on the conductor is increased by the following measures:

1. increases in the current;
2. increases in the magnetic field strength;
3. increases in the length of the conductor sited in the magnetic field.

If the conductor in the magnetic field is in the form of a loop or a coil then a force acts on each side of the coil. These forces act in opposite directions and they combine to produce a turning effect, called a torque, on the coil. The turning action of a current-carrying coil in a magnetic field is the basis of devices such as direct current motors and electric meters.

Electric motors

An electric motor is a device for converting electrical energy to mechanical energy by using the force produced when two magnetic fields interact.

Simple d.c. Motor The simple motor illustrated in figure 11.15 is a design that works but would not be used for a practical machine. However, the essential features and the operation of a simple motor are convenient to describe and they also apply to practical motors. The coil is set in a magnetic field and is free to turn on an axle. The d.c. supply is connected to the coil via conducting 'brushes' which slide against the rotating *commutator*.

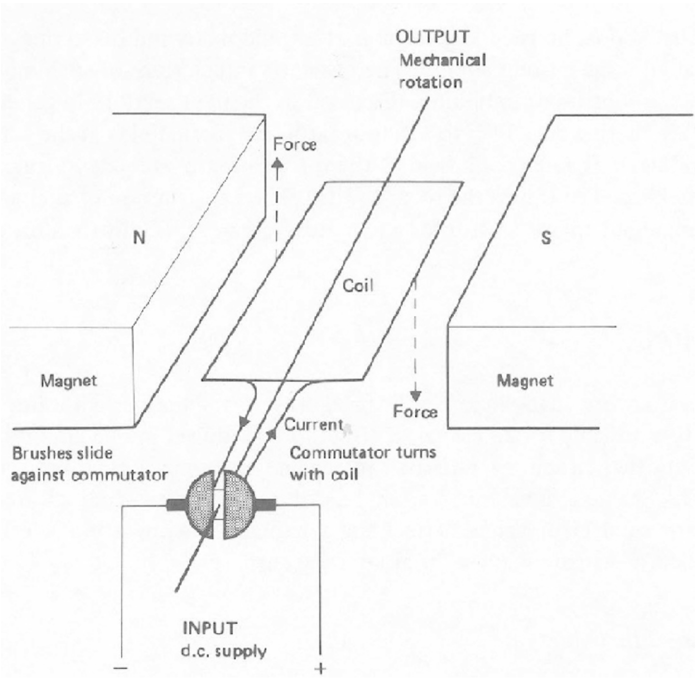


FIGURE 11.15 *Simple d.c. electric motor*

When current flows in the coil the motor effect produces forces that turn the coil. When the coil is vertical the commutator disconnects the supply and the coil continues turning by momentum. The commutator then reconnects the coil to the opposite supply terminals. This reversal of connections ensures that the same direction of force always acts on the same side of the motor. The repeating cycle of reversed connections keeps the axle turning in one direction and it can be used to do mechanical work.

Practical d.c. Motors A practical motor works on the same general principle as the simple motor but is made more efficient by additional features.

Field windings supply the magnetic field. These electromagnets are arranged in a circular form in order to keep the air gap to a minimum.

The *armature* turns on an axle inside the magnetic field and has the main coils wound upon it. More than one set of coils is wound on the same armature and a commutator, with many splits, connects the electrical supply to one coil at a time.

The connections between the field coils, the armature windings, and the electrical supply can be interconnected in different ways, which give the motor different characteristics when starting and when under load. The speed of the motor can be varied by the use of a variable resistor in series with the armature.

A.c. Motors Most household electric motors, and many industrial ones, operate from an alternating current supply. The magnetic interactions of such motors involve the properties of induction, discussed in the next section. In general the effect of alternating current is to set up rotating magnetic fields in the stator (field windings). The magnetic field of the rotor (armature) tends to follow the rotating fields and so causes the rotor to turn. The construction of such motors can be simple but speed control for a.c. motors is more difficult than for d.c. motors.

INDUCTION

Induction is a word that can mean the bringing out of an effect without physical contact. It is possible for an electrical effect to be induced in one circuit by the action of another circuit, even though there is no apparent contact between them. In fact there is always a very real link of magnetic flux. Induction is a special form of electromagnetic effect and it explains the operation of generators, transformers and many features of alternating current supply.

Electromagnetic induction

If a conductor is moved across a magnetic field then an e.m.f. is induced in that conductor. This induced electricity also occurs in the types of circuits shown in figure 11.16:

(a) In figure 11.16a a magnet is moved towards the coil and an e.m.f. is induced in the coil. A current therefore flows in the circuit and is detected by the meter. The direction of the current reverses when the direction of the magnet is reversed or the poles of the magnet are reversed. The same effects are achieved by moving the coil towards the magnet. The induction occurs when either the coil or the magnet moves.

(b) If the coil and the meter are connected directly to a d.c. supply, as in figure 11.16b, there is no induced e.m.f. If, however, a switch is inserted in the circuit then the e.m.f. changes every time the switch is put either on or off. This *self-induction* is produced when the electromagnetic field of the coil cuts across adjoining turns of the coil.

(c) If two coils are placed adjacent to one another, as in figure 11.16c, then an e.m.f. is induced in the circuit with the meter whenever the switch in the

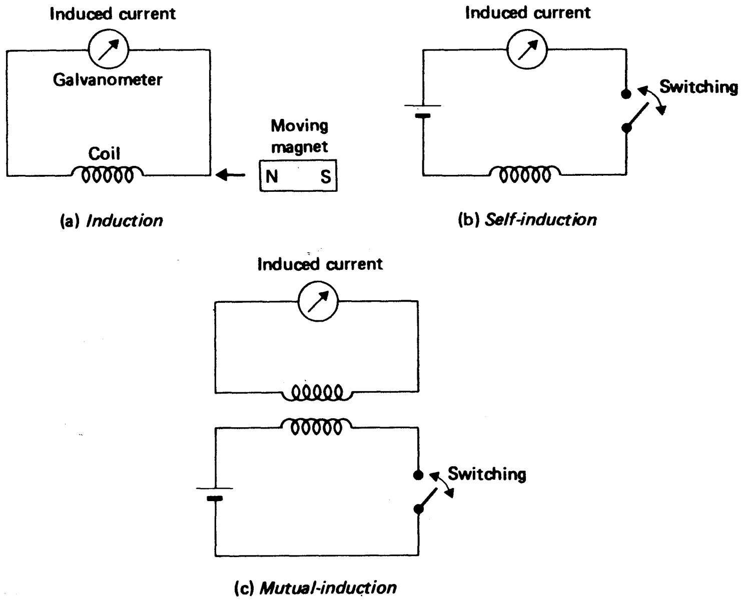


FIGURE 11.16 *Electromagnetic induction*

battery circuit is put either on or off. This *mutual inductance* is produced when the electromagnetic field of the first coil cuts the turns of the second coil. The 'flux linkage' between the two coils can be improved by using a soft-iron core between them.

Principles of induction

The different demonstrations of induction described above share the common mechanism that, in each case, the induction coil experiences a magnetic field which is changing. The change in magnetic field may be caused by a movement or by switching a circuit on or off.

General Principle of Induction

> **An electric current will be induced in a conductor which is subjected to a *changing* magnetic field.**

Magnitude of Induction The size of the induced current depends upon the following factors:

1. relative speed of movement of the magnetic field;
2. strength of the magnetic field;
3. length of conductor in the magnetic field;
4. angle between the conductor and the field.

Lenz's Law The direction of all induced currents can be predicted by Lenz's Law

The direction of the induced current is such that it will always oppose the change that produced it.

This rule applies to all methods of induction. In the simple example shown in figure 11.16a a magnet is moved towards the coil with the north pole leading. The current induced in the coil sets up a magnetic field and, by Lenz's Law, this field will oppose the approaching magnet by having its own north pole outwards. If the movement of the magnet is reversed then the induced field will also be reversed; so as to oppose the movement.

Applications of Induction Electromagnetic induction is the principle behind many important devices used for the generation, the transmission, and the application of electricity. Some examples are given below:

1. generators, for the production of electricity;
2. transformers, for changing voltage and current;
3. induction motors;
4. ignition coils, for spark in car engines;
5. hi-fi cartridges for playing records;
6. linkages in electronic circuits.

Generators

A generator is a device that converts mechanical energy to electrical energy by means of electromagnetic induction. Most of the electricity used in everyday life is generated in this manner. The change in magnetic field necessary for induction is produced by moving a coil through a magnetic field, or by moving a magnetic field past a coil. Rotational motion is usually employed. Some types of generator may be known as a dynamo or an alternator.

Simple a.c. Dynamo The simplest type of generator is the a.c. dynamo, which is shown in figure 11.17. The generator coil is set on an axle in a magnetic field and connected to metal *slip-rings* on the axle. The slip-rings make sliding contact with the stationary brushes, which carry current away from the generator. The axle is rotated by a source of mechanical energy, such as a motor, and the coil moves through the magnetic field. The coil experiences a changing magnetic field, an e.m.f. is induced in the coil, and a current flows. The current is led away from the generator via the slip-rings and the brushes.

Maximum current is generated twice per revolution as the coil cuts the field at right angles, which happens when the coil is horizontal. Zero current is generated when the coil is vertical. The current varies from zero to maximum

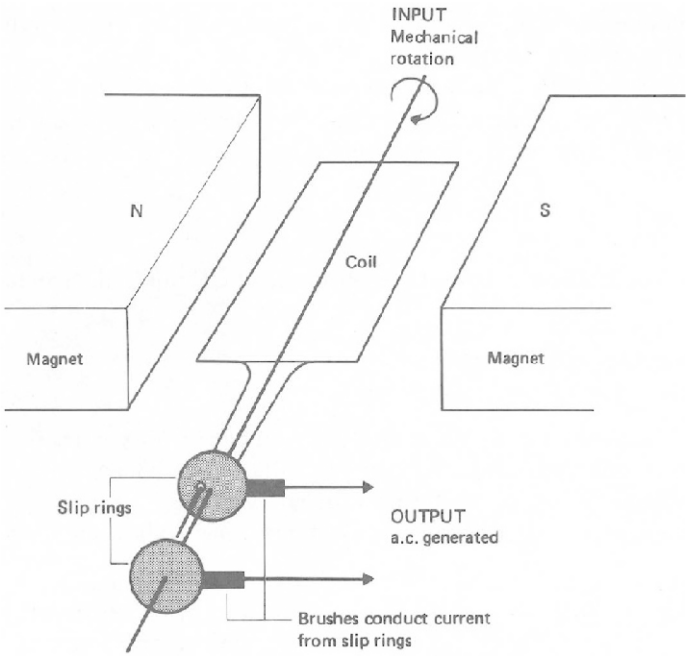


FIGURE 11.17 *Simple a.c. dynamo*

depending upon the angle at which the coil cuts the magnetic field. As the coil rotates through one revolution it cuts the magnetic field in two different directions and the induction reverses direction.

The e.m.f. and the current produced by this generator is therefore continuously 'alternating' with every revolution of the coil. The output of this 'alternator' is in the shape of a sine wave, as shown in figure 11.19.

d.c. Generator The current from a battery has a steady value in one direction. To obtain this sort of 'direct current' from a generator it is necessary to replace the slip-rings by a commutator which reverses the connections every half turn and gives a current flowing in one direction only. This current will still fluctuate in value and to obtain a virtually steady flow of current the commutator is split into many sections and connected with up to 30 different coils. The construction is the same as for the d.c. motor and some machines can act as both generator and motor, at different times.

Practical a.c. Generators A large practical a.c. generator or alternator works on the same general principle as the simple generator but its construction is different.

The *stator* is the stationary frame to which are fixed the output windings that produce the current. No moving contacts are necessary so large voltages and currents can be generated.

The *rotor* turns inside the stator and contains the magnetic field coils. The d.c. supply necessary for these electromagnets is supplied by a separate self-starting *excitor* dynamo, run on the same axle.

Transformers

A transformer is a device that uses the principle of electromagnetic induction to:

(1) step-up or step-down voltage;
(2) step-up or step-down current;
(3) isolate a circuit from an a.c. supply.

A major reason for using a.c. in electricity supplies is the relative simplicity and efficiency of transformers for changing voltage, as explained in the section on power transmission. A transformer does not work on d.c. supply.

The construction of a common type of transformer is shown in figure 11.18.

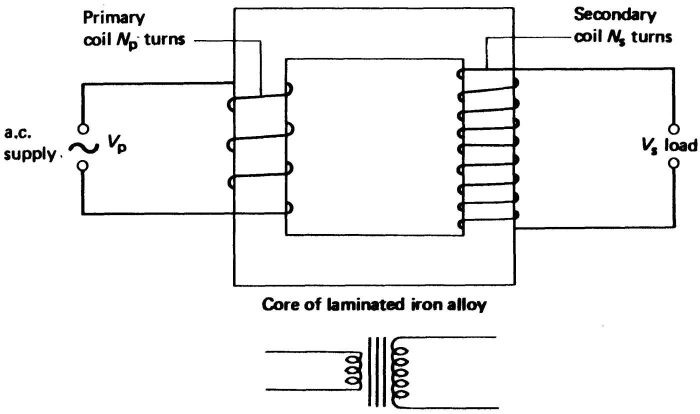


FIGURE 11.18 *Double-wound step-up transformer*

The primary coil is connected to an a.c. supply and sets up a magnetic field which is continuously changing with the alternating current. The secondary coil experiences this changing magnetic field and produces an induced e.m.f. which can then be connected to a load. The induced e.m.f. alternates in form and frequency with the e.m.f. of the supply frequency but the ratio of the two e.m.f.s is proportional to the ratio of the turns on the two windings.

Transformer Equation

$$\boxed{\frac{V_s}{V_p} = \frac{N_s}{N_p}}$$

where

V_s = e.m.f. induced in the secondary coil (V)

V_p = e.m.f. applied to the primary coil (V)

N_s = number of turns on the secondary coil

N_p = number of turns on the primary coil

A transformer with twice the number of secondary turns as primary turns will, for example, 'step-up' the secondary voltage to twice the primary voltage. If the connections to such a transformer are reversed the transformer could be used as a 'step-down' transformer which then halves the applied voltage. In an 'isolating transformer' the primary and secondary voltage may be the same.

Transformers are very efficient machines and their power output is almost equal to their power input. If, for simplicity, it is assumed that there are no power losses then

Output power = Input power

or

$$I_s V_s = I_p V_p$$

where

I_s = current in secondary coil (A)

V_s = e.m.f. of secondary coil (V)

I_p = current in primary coil (A)

V_p = e.m.f. of primary coil (V)

This relationship shows that if a transformer increases the voltage then the current must decrease by the same ratio, so as to conserve energy. In practice, some energy is lost in a transformer by heating in the coils and in the core. *Eddy currents* are circulating currents which are induced in the core and they are minimised by constructing the core from separate laminations so that it presents a high magnetic resistance.

*   *   *   *   *

Worked example 11.4

A transformer has 600 turns on the primary coil and 30 turns on the secondary coil. An e.m.f. of 240 V is applied to the primary coil and a current of 250 mA flows in it. Calculate: (a) the e.m.f. of the secondary coil; and (b) the current flowing in the secondary coil (assuming that the transformer is 100 per cent efficient).

(a) $N_p = 600$, $V_p = 240$, $N_s = 30$, $V_s = ?$

Using $(V_s/V_p) = (N_s/N_p)$

$$\frac{V_s}{240} = \frac{30}{600}, \quad V_s = \frac{30}{600} \times 240 = 12 \text{ V}$$

Secondary e.m.f. = **12 V**

(b) $V_p = 240$ V, $I_p = 0.25$ A, $V_s = 12$ V, $I_s = ?$

Using $I_s V_v = I_p V_p$

$$I_s \times 12 = 0.25 \times 240; \quad I_s = \frac{0.25 \times 240}{12} = 5 \text{ A}$$

Secondary current = **5 A**

*   *   *   *   *

Alternating current properties

The e.m.f. induced in an a.c. generator is constantly changing and reversing, so the current produced also changes. The alternating cycle produced is shown in figure 11.19 and to describe the nature of this alternating output some additional terms are needed.

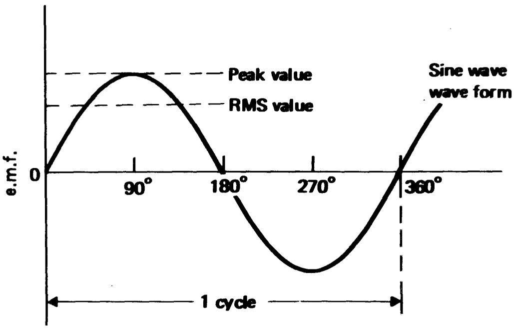


FIGURE 11.19 *Alternating current output*

Frequency

FREQUENCY (f) is the number of repetitions, or cycles, of output per second.

UNIT: hertz (Hz).

For public supplies in Britain and most other countries the frequency is 50 Hz; in the United States the frequency is 60 Hz.

Peak Value The peak value is the maximum value of alternating voltage or current, measured in either direction. The peak values occur momentarily and only twice in a complete cycle, as shown in figure 11.19.

RMS Value The simple mathematical average of a sine wave output is zero. But an alternating supply does produce an effective voltage or current and this is measured by RMS values.

A ROOT MEAN SQUARE (RMS) value of alternating current is that value of direct current that has the same heating effect as the a.c. current.

A 1 kW fire, for example, produces the same heating effect using 240 V alternating current as it does using 240 V direct current. The RMS value is found mathematically by taking many instantaneous peak values, squaring them, taking the average of the squares, then taking the square root. The relationship between the values is found to be

$$\boxed{\text{RMS} = 0.707 \text{ peak}}$$

The domestic supply a.c. voltage of 240 V RMS has a peak value of 339 V. It is assumed that values quoted for a.c. supplies are always RMS values, unless it is stated otherwise.

Power Factor The voltage and the current of an a.c. supply are *in phase* when both have their peak values and zero values occurring at the same time. The power used by an a.c. circuit that is in phase is calculated as the product of the RMS values of current and voltage; similar to d.c. power.

Some a.c. circuits contain components that cause a *phase shift*, where either the voltage or the current leads or lags the other. In such a circuit some of the energy supplied as *apparent power* is lost in heating the circuit and does not appear as effective power or *active power*. The power factor expresses the ratio between the two forms of power

$$\textbf{POWER FACTOR (PF)} = \frac{\text{Active power (watts)}}{\text{Apparent power (volt-amperes)}}$$

$$= \text{cosine } \theta$$

where θ is the angle between current and voltage.

The power factor has a maximum value of 1. Most a.c. equipment is rated by its apparent power together with a power factor. Supply authorities have to generate the apparent power but can only charge for the active power which appears on the meters, so they set minimum allowable values for the power factor (0.85 for example).

Devices with simple resistance, such as a heater, have a power factor of 1 and their active power is the same as their apparent power. Devices with induction coils, such as motors for example, have power factors less than 1. Low power factors can be improved by adding a capacitance device in parallel to cancel the inductance.

Three-phase supply

The output from a simple a.c. generator, shown in figure 11.19, is a *single-phase* supply. Practical supplies of electricity are usually generated and distributed as a *three-phase* supply, which is – in effect – three separate single-phase supplies each equally out of step, as shown in figure 11.20. The generator is essentially composed of three induction coils instead of one, each coil being displaced from one another by 120 °. The three phases can be interconnected in different ways for different purposes, as shown in figure 11.21.

A *delta* connection is used for larger loads, such as three-phase motors. The

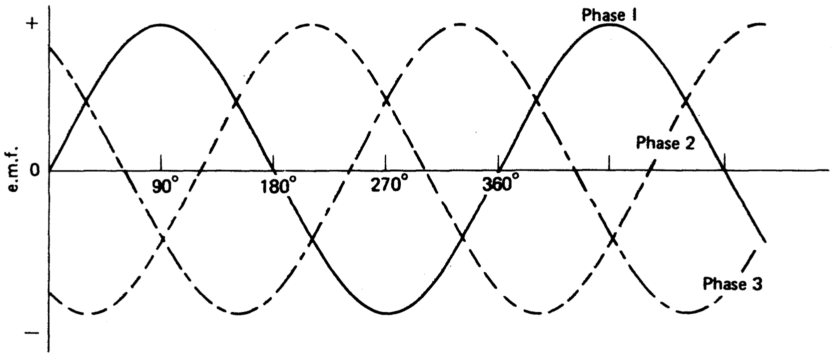


FIGURE 11.20 *Three-phase alternating current*

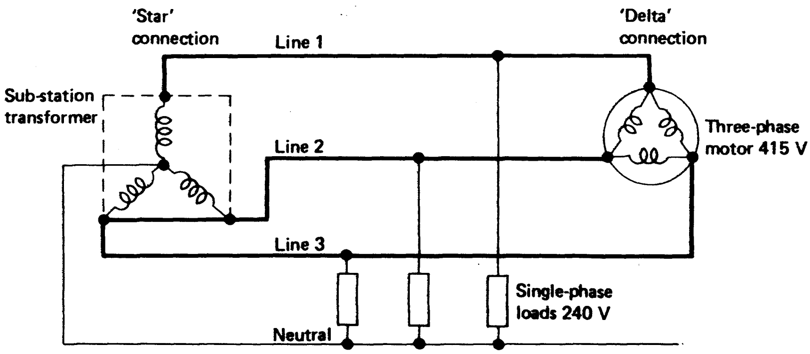


FIGURE 11.21 *Three-phase, four-wire a.c. supply*

voltage across any two phases (the *line* voltage) is 1.73 ($\sqrt{3}$) times the voltage between any one phase and earth.

A *star* connection is used for relatively small loads, such as households. They are connected to one phase and to the neutral to provide a 240 V supply. If the single-phase loads are evenly balanced then the return current in the neutral cable is zero.

Three-phase supplies are economical in their use of conductors and can supply more power. Only three cables need to be used for the three-phase supply, instead of the six cables that would be needed for three separate single-phase supplies. A device such as a motor which is designed to make use of three phases receives more energy per second than by one phase; it is also smoother in its operation.

POWER SUPPLIES

A public supply of electrical energy is one of the most important services in a modern society. Manufacturing, building services, transport and communications are all dependent upon electricity supplies. Large electric power systems require significant investments in building and engineering; they have a big impact upon the look of the landscape and any breakdown greatly disrupts people's lives. It may be necessary in the future to make changes in the design of electric power systems and in the use of their output but, some form of electricity supply will always be needed.

A complete power system is a collection of equipment and cables capable of producing electrical energy and transferring it to the places where it can be used. A power system is made up of three main operations:

1. *generation* of electricity;
2. *transmission* of electricity over sizeable distances;
3. *distribution* of electricity to individual consumers.

The overall energy efficiency of a power system is about 30 per cent.

Power stations

All power stations generate electrical energy by using electromagnetic induction; an e.m.f. is produced in a coil which experiences a changing magnetic field. The mechanical energy required is obtained using the heat from burning fossil fuels and from nuclear reactions, or obtained from the energy of moving water. A turbine is a device that produces rotational motion from the steam or running water and turns the axle of the generator.

A typical generator in a thermal power station turns at 3000 rev/min and has an excitor dynamo mounted on the same shaft. The output varies but a large

500 MW set commonly generates 23 000 A at 22 kV. The cooling of the generators, by liquid or gas, is an important part of their engineering.

Thermal Power Stations Thermal power stations use heat energy to drive the generators. The heat is obtained by burning fuels such as oil, coal or gas. The components of a thermal station are outlined in figure 11.22. The boiler burns the fuel and heats water to produce high-pressure, high-temperature steam. The steam is directed onto the blades of a high speed turbine which produces mechanical energy and turns the generator. The steam is condensed and the water returned to the boiler.

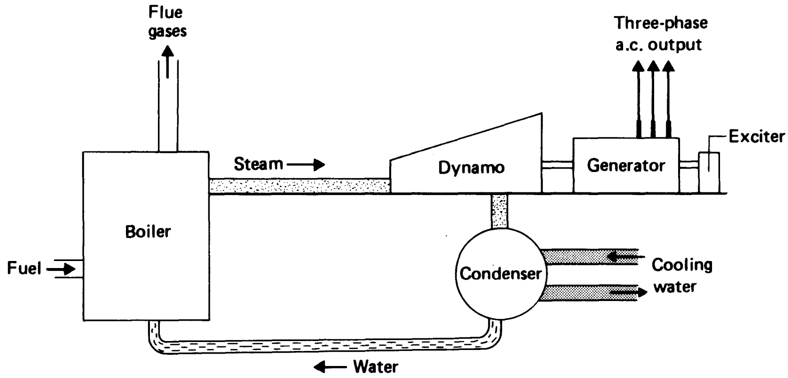


FIGURE 11.22 *Thermal power station scheme*

The efficiency of the boiler is the main limitation of the system but modern techniques, such as fluidised-bed combustion offer some improvements. A thermal power station can, however, use low-quality coal and the ash recovered from the boiler can be used as a building aggregate. The condensation of the steam from the turbines requires large quantities of cooling water from a river, otherwise large and unsightly cooling towers have to be built.

The advantages of a thermal power station include the fact that they can be sited near the demand for their electricity and so save on the cost of transmission lines. It is also possible for some of the waste heat from the condensation process to be used for industrial purposes or for district heating of buildings. A disadvantage of thermal power stations is the relatively high cost of their fuels and the fact that their fuel supply will eventually be limited. The life of such a station is only about 20 years.

Nuclear Power Stations Nuclear power stations are thermal stations where the heat energy is released from a nuclear reaction rather than by burning a fossil fuel. Radioactive elements, such as uranium and plutonium have unstable nuclei which emit neutrons. These neutrons split neighbouring atoms, thus releasing other neutrons and producing heat. This *fission* reaction is controlled and prevented from becoming a chain reaction by using moderator materials, such as carbon, which absorb neutrons without reaction.

A nuclear reactor consists of a central container holding the radioactive fuel elements which are surrounded by control rods of the moderator material. The withdrawal of some control rods starts the reaction and the insertion of extra control rods can stop the reaction. The heat generated by the reaction is carried by a coolant from the core to a heat exchanger which produces steam for the turbines. Because the core and the coolant emit dangerous radiation they must be well protected.

The *pressurised water reactor* (PWR) is a common type of reactor in practical use. The coolant in the reactor is water which is kept at high pressure to prevent it boiling. The *advanced gas-cooled reactor* (AGR) uses carbon dioxide gas as the coolant. *Breeder reactors* are reactors that produce more fuel than they consume, as a result of the nuclear reaction.

The advantage of nuclear power stations is that they reduce dependence upon fossil fuels, and their operating costs can be lower than those of thermal stations. The disadvantages of nuclear power stations centre around the harm that escaped radioactive fuels, coolants and waste products can cause to people and their environment. The safety of nuclear reactors depends upon the reliability with which they can be built and operated under practical conditions.

Hydroelectric Power Stations Hydroelectric power stations use the kinetic and potential energy of running water to drive the generators. A large quantity of water at a height is required to provide enough energy. The original source of this energy is sunshine which lifts the water by means of evaporation. A dam usually provides both the head of water and a reservoir of stored water. The water flows down penstock pipes or tunnels and imparts energy to the water turbines which turn the generators.

The advantages of hydroelectric power stations are that their energy source is free, they have a long operating life and they need few staff. The disadvantages of hydroelectric stations include the very large capital investment on civil engineering work. Suitable sites for such stations are limited and usually need long and expensive transmission lines to consumers.

Transmission systems

Electrical energy has the useful property of being easily transferred from one place to another. A transmission system, as shown in figure 11.23, consists of conducting cables and lines, stations for changing voltages and for switching, and a method of control. The energy losses in the system must be kept to a minimum.

Alternating current is used in nearly all modern power transmission systems because it is easy to change from one voltage to another, and the generators and motors involved in a.c. are simpler to construct than for direct current. To obtain high transmission efficiency the current needs to be kept low because the heating losses in a line increase with the square of the current ($P = I^2R$). Large currents also require thick conductors which are expensive and heavy. To transmit large amounts of power at low current there must be a high voltage ($P = IV$). Transformers are used for obtaining the necessary high voltages and large air gaps are used to supply the high insulation that is needed at high voltage.

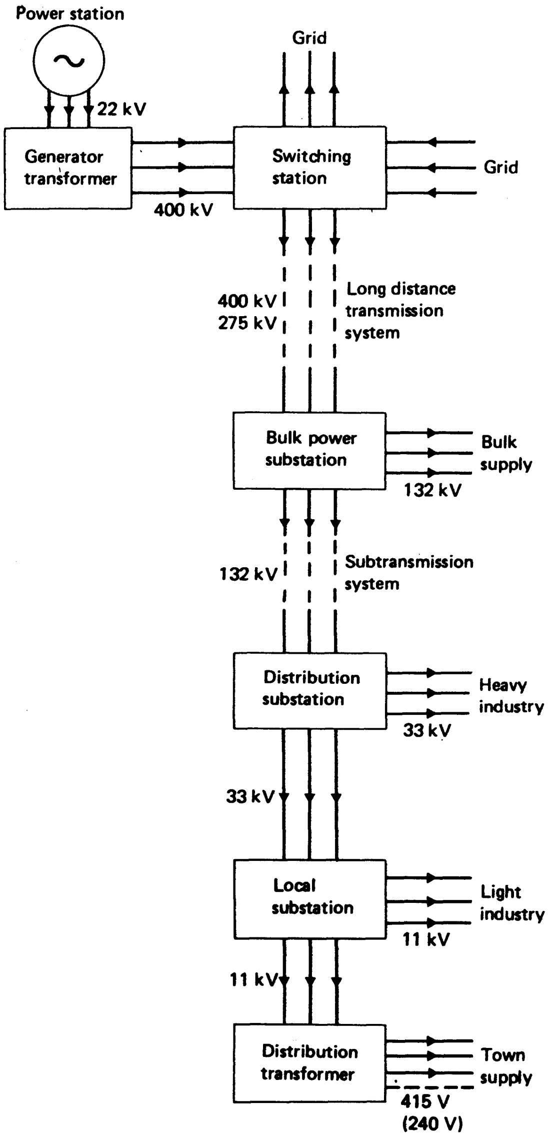


FIGURE 11.23 *Typical power distribution*

Transmission Lines The conductors for overhead transmission lines are made of aluminium with a steel core added to give strength. The transmission of three-phase supply requires three, or multiples of three, conductors; six being a common number in use.

Transmission towers ('power pylons') are needed to keep the lines spaced in the air. Air is a convenient cheap insulator but higher voltages require larger air gaps in order to prevent short circuits through the air. The lines are suspended from the towers by solid insulators made of porcelain or glass. Transmission lines operate at voltages of 132 kV and above. The United Kingdom supergrid is at 400 kV and some countries have 735 kV systems.

In a buried cable the conductor must be insulated for its whole length and protected from mechanical damage. High voltage underground cables need special cooling in order to be efficient. It is possible to bury 400 kV transmission cables but the cost is 10 to 20 times greater than for overhead lines.

Sub-stations and Switching Power transmission systems need provision for changing voltages, for re-routing electricity and for protecting against faults.

At *sub-stations* the voltages are changed up or down as required using large transformers which are immersed in oil for the purpose of cooling as well as for insulation. At a power station, for example, a 1000 MVA transformer might step-up 22 kV from the generators to 400 kV for the transmission lines. At distribution sub-stations the 400 kV is stepped down to 132 kV, 33 kV, and 11 kV.

Switching sub-stations are sub-stations where a number of transmission lines are interconnected enabling electrical energy to be routed to where it is required. When lines carrying large currents are disconnected the currents form arcs of flame which melt contacts. *Circuit breakers* are used to connect or disconnect the transmission lines and arcs are extinguished by immersion in oil or by blasts of air. Protection systems are devices which act as fuses by sensing faults on a line and then immediately isolating the line.

Transmission control

An electric power grid is a large system of interconnected power stations and consumers. The output from any power station is not dedicated to just one area but can be distributed to other areas as required.

Advantages of Grids

1. Large power stations with lower operating costs are possible.
2. Sudden local demands for power can be supplied by a number of power stations.
3. The effects of breakdowns in generating plant and transmission lines can be minimised.

4. Periods of low demand, such as night time, can be supplied by those plants with the lowest operating costs.

Disadvantages of Grids

1. It is difficult to keep all the generators working at the same frequency, which is necessary for the transfer of power.
2. Surplus heat from thermal power stations is often wasted.

General distribution

At suitable junctions or at the ends of transmission lines the voltage is stepped down, as indicated in figure 11.23. In the British system the voltage is reduced from 400 kV (or 275 kV) to 132 kV. The electricity is distributed at this voltage by a subtransmission system of overhead lines to the distribution substations. At these stations the voltage is reduced to 33 kV and 11 kV for distribution by underground cable.

Large industrial consumers are supplied at 33 kV while smaller industrial consumers receive 11 kV. Small transformer stations in residential and commercial areas step the voltage down to the final 415 V three-phase, 240 V single-phase supply, which was explained in an earlier section of this chapter. The three-phase supply is distributed by three phase cables (red, yellow and blue) plus a neutral cable. Some commercial consumers are connected to all three cables of the supply. Households are connected to one of the phase cables and the neutral. Consumers are balanced between the three phases as evenly as possible by connecting consecutive houses to different phases in turn, for example.

Because perfect balance is not achieved the neutral cable carries a small amount of return current and is earthed at the distribution transformer. To ensure true earth potential, each consumer is supplied with an extra earth cable for attaching to the metal casing of electrical appliances. If an insulation fault causes a connection to this earth then a large current flows, immediately blows the fuse, and protects the user.

United Kingdom electrical supply

Most of the electricity in the United Kingdom is generated by thermal power stations which use oil or coal as the fuel. Some hydroelectric power is generated, mainly in Scotland. The number of power stations has been decreasing as larger modern stations are commissioned.

The *National Grid* is the system of interconnected generating stations, transmission lines, and consumers. In 1982 the system contained up to 120 power stations giving a maximum total output of 60 000 MW. This power was distributed by over 12 000 km of main transmission lines. The National Grid Control Centre in London directs the power flow in the grid with the aid of plans prepared by local control centres. The daily predictions of power demand take account of seasonal trends, the weather, the day of the week and special factors such as television programmes.

The *Central Electricity Generating Board* (CEGB) owns and operates the power stations and main tranmission lines in England and Wales. The CEGB is responsible for the bulk supply of electricity to the Area Boards but it does not sell direct to consumers except the railways.

The twelve *Area Electricity Boards* of England and Wales are responsible for the distribution networks and for the retail sale of electricity to their customers. Scotland has two electricity boards and Northern Ireland has one board; each of these boards is responsible for generation and transmission, as well as distribution, in their respective areas.

EXERCISES

1 The potential difference across a certain resistor in a television circuit is found to be 450 V when a current of 150 mA is flowing through the resistor. Calculate the value of this resistor.

2 Draw the circuit diagram of a 3 Ω and a 4 Ω resistor connected in series together with a potential difference of 14 V applied across them. Calculate:
(a) the total current flowing in the circuit; and
(b) the voltage drop across the 3 Ω resistor.

3 Draw the circuit diagram of a 5 Ω and a 20 Ω resistor connected together in parallel with a potential difference of 80 V applied across them. Calculate:
(a) the total resistance of the circuit;
(b) the total current flowing in the circuit; and
(c) the current flowing in the 5 Ω resistor.

4 A 20 m length of cable carries a continuous current of 10 A. At this current the cable has a resistance of 4 mΩ/m. Calculate:
(a) the total power loss in this cable; and
(b) the total energy lost in the cable during 24 hours.

5 Calculate the current which flows in a 60 W light bulb when it is connected to a 240 V supply. How many such bulbs, wired in parallel, could be connected to a socket which is fitted with a 3 A fuse?

6 A 136 l hot water storage cylinder is heated by a 240 V electric element which has a resistance of 15 Ω. Assuming that no energy is lost in the heating process calculate the following:
(a) the power rating of the element;
(b) the energy needed to raise the temperature of the entire contents from 5 °C to 60 °C; and

(c) the time taken to raise the temperature as above.
Given: density of water is 1000 kg/m^3 and specific heat capacity of water is 4200 J/kg °C.

7 A transformer with 200 turns in the primary winding is to step-up voltage from 12 V to 240 V. Assuming that the transformer is 100 per cent efficient calculate:
(a) the number of turns needed in the secondary winding; and
(b) the current flowing in the primary winding when a 100 W lamp is connected to the output.

8 The apparent power rating of an a.c. motor is 4000 VA and it has a power factor of 0.85. Calculate:
(a) the output power of the motor;
(b) the current drawn from the 240 V mains; and
(c) the peak value of this current.

ANSWERS

1 3 kΩ
2 2 A, 6 V
3 4 Ω, 20 A, 16 A
4 8 W, 691.2 kJ or 0.19 kWh
5 0.25 A, 12 bulbs
6 3840 W, 31.42 MJ, 136.4 min
7 4000 turns, 8.33 A
8 3400 W, 16.67 A, 23.57 A

12 Water Supplies

Water is as essential for life as food and air. Water is also an important requirement for many industries. The supply of suitable quantities of good water is a fundamental service in a community and requires major financial and engineering investments in systems for the collection, storage, treatment and distribution of the water. The pumping of water necessary in a supply system also needs significant amounts of energy.

This chapter introduces some of the properties of liquids and uses these properties as a basis for analysing the flow of water in pipes and drains. The sources and the characteristics of natural water are described and current methods of water treatment are summarised.

FLUIDS AT REST

A fluid is a material whose particles are free to move their positions – liquids and gases are both fluids. Although liquids and gases are different states of matter they share some common properties as fluids. These sections on fluid properties are directed towards understanding the flow of water in pipes but it is useful to remember that the general principles described also explain other effects, such as the flow of air in ventilation ducts.

Pressure

The pressure on a surface is defined as the force acting at right angles on that surface divided by the area of the surface. The force that acts on an area A which is submerged at depth h in a fluid is equal to the weight of the column of liquid or gas above that area. The pressure is then this weight divided by the area.

$$\text{Force} = \text{weight} = \text{mass} \times \text{gravitational acceleration}$$

$$= mg$$

$$\text{Mass} = \text{density} \times \text{volume}$$

$$= \rho V$$

Volume $= Ah$

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{mg}{A} = \frac{\rho Vg}{A} = \frac{\rho Ahg}{A}$$

The pressure at any point on the area is the same ratio, calculated for a very small area. So that in general, the pressure at any point in a fluid is given by the formula

$$\boxed{p = \rho gh}$$

where

p = pressure at a point in a fluid (Pa)

ρ = density of the fluid (kg/m^3)

g = gravitational acceleration = 9.81 m/s

h = vertical depth from surface of fluid to the point (m)

Units of pressure The pascal (Pa) is the SI unit of pressure. By definition:

1 pascal = 1 newton/square metre (N/m^2)

Pressure 'head' in metres. Because the values of density and gravitational acceleration in the pressure equation are usually constant it is a common working practice to quote only the height associated with the pressure. *Specific weight* (w) of a fluid is the product of density and gravitational acceleration

$$w = \rho g$$

Principles of Fluid Pressure

1. Pressure at a given depth of fluid is equal in all directions.
2. Pressure always acts at right angles to the containing surfaces.
3. Pressure is the same at points of equal depth, irrespective of volume or shape.

In figure 12.1 for example, the pressure at all three points A, B and C, is the same and is not affected by the irregular shapes involved.

Pressure measurement

Absolute pressure is the value of a particular pressure measured in units above an absolute zero of pressure.

Gauge pressure is the value of a particular pressure measured in units above or below the atmospheric pressure.

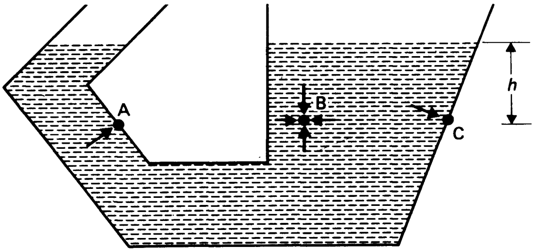


FIGURE 12.1 *Principles of pressure*

Manometer The manometer is an instrument that measures pressure by comparing levels in a U-tube containing liquid, as shown in figure 12.2. Water is a convenient liquid; oils may be used to measure some gases, and mercury is used for measuring high pressures.

In figure 12.2 the pressure at point A must be the same as the pressure at point B. The pressure at point B is produced by a column of liquid, height h, plus atmospheric pressure. So that

Measured pressure = Atmospheric pressure + $\rho g h$

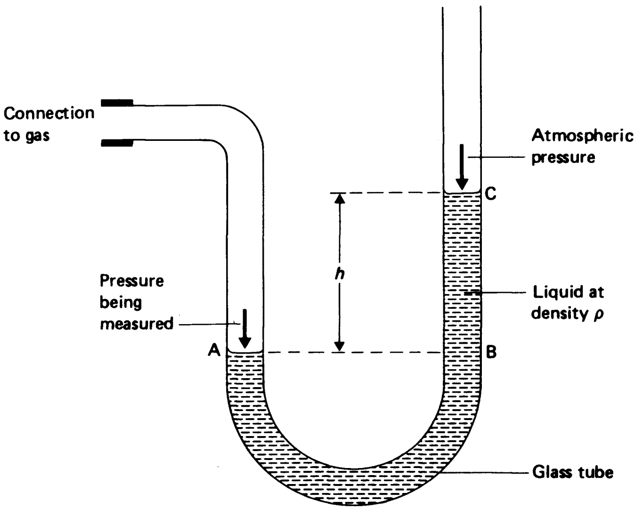


FIGURE 12.2 *Manometer*

Bourdon Gauge The Bourdon gauge is an instrument that measures pressure by means of the changing curvature of a bronze tube, as shown in figure 12.3. As the pressure increases the tube tends to straighten and, by some mechanical linkage, it moves a needle on a scale. The gauge needs calibrating against some absolute form of measurement.

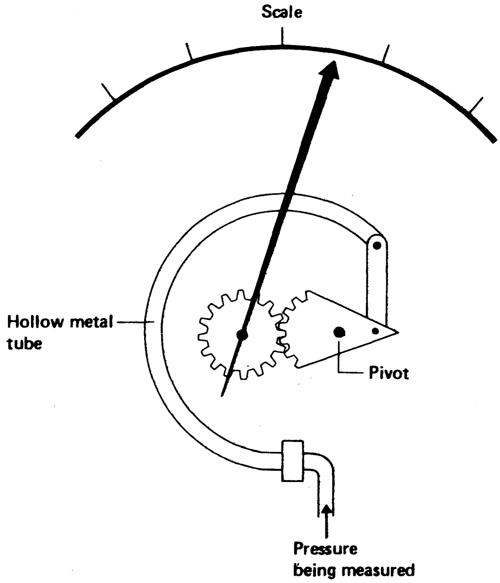


FIGURE 12.3 *Bourdon gauge*

Force on immersed surfaces

The force on a surface can be calculated from the pressure on the surface and the area of the surface. A submerged plate is subject to different pressures and forces acting at many different points. The total force or thrust on a submerged plate is given by the expression:

$$F = p_c A$$

where

F = total resultant force or thrust (newtons N)

p_c = pressure at the centre of area (centroid) of the immersed area (Pa)

A = total immersed area of the plate (m^2)

For a rectangular area, as shown in figure 12.4, the centre of area is positioned at half the immersed depth.

The *centre of pressure* is the point where the line of action of the resultant force passes. The centre of pressure is always located below the centre of area of the figure. For a rectangular surface the centre of pressure is at $\frac{2}{3}$ of the immersed depth, measured from the top.

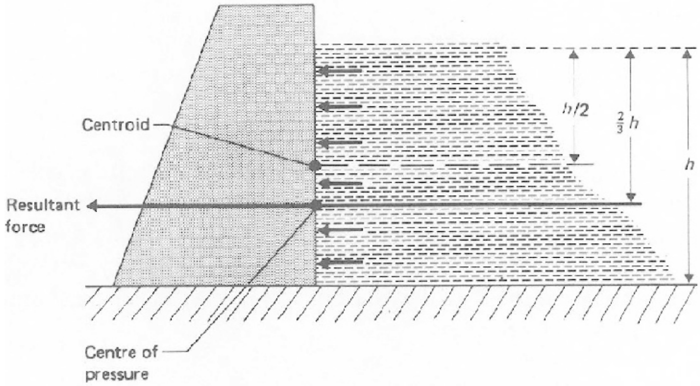


FIGURE 12.4 *Force on an immersed surface*

*   *   *   *   *

Worked example 12.1

A rectangular sluice gate is 1.6 m wide and is retaining water to a depth of 800 mm. Calculate the lateral thrust on the gate produced by the water. Given: density of water is 1000 kg/m, and gravitational acceleration is 9.81 m/s.

ρ = 1000 kg/m, g = 9.81 m/s, h = depth to centre of area = 0.4 m.

$A = 1.6 \times 0.8 = 1.28\ \text{m}^2$

Using $p_c = \rho g h$

$= 1000 \times 9.81 \times 0.4 = 3924$ Pa

Using $F = p_c \times A$

$= 3924 \times 1.28 = 5023$

Force on gate = **5023 N**

*   *   *   *   *

FLUID FLOW

The behaviour of moving fluids is complex and not always fully understood. However, the construction of water supplies, drainage and ventilation systems requires a knowledge of fluid flow. The theoretical study of fluids (hydrodynamics) is usually combined with experimental studies (hydraulics) to produce designs for practical situations.

Types of fluid flow

One method of classifying fluid movement is to divide it into two major types: laminar and turbulent flow.

Laminar Flow Laminar or *streamline* flow produces orderly flow paths in the same direction. All particles move in fixed layers at a constant distance from the wall and they do not cross one another's path. For the full pipe shown in figure 12.5 the particles at the centre have the highest velocity and some microscopic particles at the boundary have zero velocity. In general, laminar flow occurs only at low velocities.

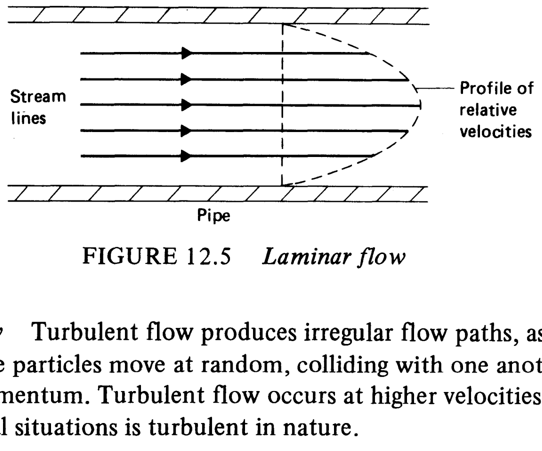


FIGURE 12.5 *Laminar flow*

Turbulent Flow Turbulent flow produces irregular flow paths, as shown in figure 12.6. The particles move at random, colliding with one another and exchanging momentum. Turbulent flow occurs at higher velocities and most flow in practical situations is turbulent in nature.

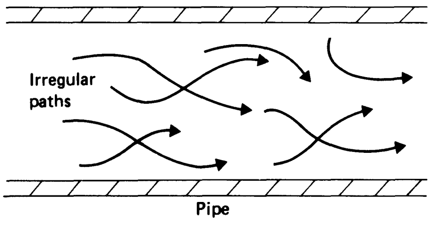


FIGURE 12.6 *Turbulent flow*

Transitional Flow Between the states of laminar flow and turbulent flow there is a transitional zone where the nature of the flow is complex. The following factors cause laminar flow to change to turbulent flow:

1. increase in velocity above the *critical velocity*;
2. increase in pipe diameter;
3. decrease in viscosity ('stickiness').

Reynolds' Number (R_e) is used to predict whether a particular flow of fluid will be laminar or turbulent in nature.

$$R_e = \frac{\rho v D}{\mu}$$

where

ρ = density of the flowing fluid (kg/m^3)

v = average velocity of fluid past a cross-section (m/s)

D = diameter of the pipe (m^2)

μ = coefficient of absolute viscosity (Ns/m)

If R_e is less than 2000, then the flow is laminar. If R_e is greater than 2000, then the flow is transitional or turbulent.

Flow rate

The amount of liquid flowing in a pipe or in a channel depends upon the dimensions of the pipe and upon the velocity of the liquid flow. This flow capacity can be described as the *discharge* or flow rate.

FLOWRATE (Q) is the volume of water flowing per second.

UNIT: cubic metres per second (m^3/s) or litres per second (l/s) where $1\ m^3/s = 1000\ l/s$.

By definition

$$\boxed{Q = \frac{V}{t}}$$

where

Q = flow rate (m^3/s)

V = volume of liquid passing a point (m^3)

t = time taken for the volume to pass the point (s)

Consider liquid flowing with an average velocity v in a pipe of uniform cross-sectional area A. If the pipe discharges a length of l of liquid in each second then the volume of water flowing per second is given by the following expression.

$$Q = \frac{V}{t} = \frac{lA}{t}, \quad \text{but also } v = \frac{l}{t}$$

so $$\boxed{Q = VA}$$

where

Q = flow rate (m^3/s)

v = average velocity of flow (m/s)

A = cross-sectional area of pipe (m^2)

Continuity Equation Figure 12.7 shows a pipe, which smoothly decreases in cross-sectional area. If the liquid flowing in the pipe is incompressible and does not vary in density then the mass of liquid flowing past each point must remain constant. The flow rate at each point in the pipe must be the same.

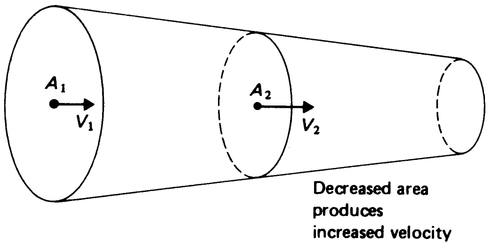


FIGURE 12.7 *Continuity of flow*

That is

$$Q_1 = Q_2$$

so

$$V_1 A_1 = V_2 A_2$$

The practical result of this continuity equation is that when the diameter of a pipe decreases then the velocity of the flow in the pipe increases.

* * * * *

Worked example 12.2

A storage tank measuring 2 m by 2 m is filled to a depth of 1.5 m in 5 min by a supply pipe with a diameter of 100 mm which runs full bore. Calculate:
(a) the flow rate in the pipe; and
(b) the average velocity of flow in the pipe.

(a) $Q = ?$ $V = 2 \times 2 \times 1.5 = 6\ \text{m}^3$, $t = 5 \times 60 = 300$ s

Using $Q = (V/t) = (6/300) = 0.02$

Flow rate = $\mathbf{0.02\ m^3/s}$

(b) $Q = 0.02\ \text{m}^3/\text{s}$, $v = ?$ $A = \pi \times (0.05)^2$

Using $Q = vA$

$0.02 = v \times \pi(0.05)^2$ $v = \dfrac{0.02}{\pi(0.05)^2} = 2.546$

velocity = **2.546 m/s**

* * * * *

Energy of liquids

The energy possessed by a moving liquid is made up of the three components now listed and indicated in figure 12.8:

A *Potential energy* the energy associated with a mass of liquid at a height above a reference level (datum).
B *Pressure energy* the energy or the work associated with moving a mass of liquid by a force.
C *Kinetic energy* the energy associated with a mass of liquid having a velocity.

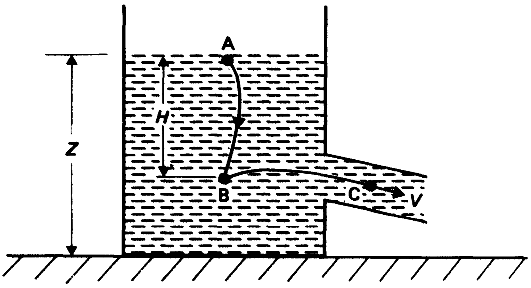


FIGURE 12.8 *Energy components of a liquid*

The energy components of a moving liquid are usually quantified in terms of equivalent 'heads' of liquid, measured in metres.

A *The datum head* $= z$, is a measure of potential energy.
B *The pressure head* $= H$, is a measure of pressure energy.
C *The velocity head* $= v^2/2g$, is a measure of kinetic energy.

Bernoulli's theorem

A particle of fluid, as shown in figure 12.8, loses potential energy but gains pressure energy when it is lowered from point A to point B in figure 12.8. If the particle gains kinetic energy in moving from point B to point C then it must lose some of its pressure energy or potential energy. This is a particular example of the general law of conservation of energy, which states that the total energy of a closed system must remain constant. When this principle is applied to moving fluids it is stated as **Bernoulli's Theorem**

The total energy possessed by particles of a moving liquid is constant.

This statement assumes that there is no loss of energy from the liquid by effects such as friction and can be re-stated as

Potential energy + Pressure energy + Kinetic energy = Constant

Referring to figure 12.9, and writing effective pressure heads, the constancy of energy can also be written as *Bernoulli's Equation*

$$z_1 + H_1 + \frac{v_1^2}{2g} = z_2 + H_2 + \frac{v_2^2}{2g}$$

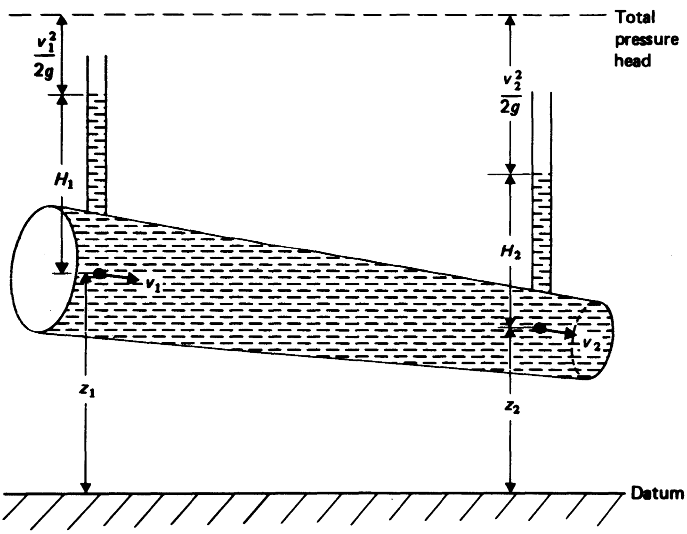


FIGURE 12.9 *Total pressure of moving fluid*

Pressure and velocity

A horizontal pipe has a constant datum head or potential energy, so that Bernoulli's expression simplifies to

Pressure energy + Kinetic energy = Constant.

For example, if the kinetic energy (the velocity) of flowing water increases then the pressure energy must decrease. As a general rule

The pressure of a moving fluid decreases when its velocity increases.

This principle, which is derived from Bernoulli's Theorem, explains a number of important effects that are associated with flowing liquids and gases. The shape of an aerofoil, such as an aircraft wing for example, causes the flowing air to have a higher velocity at the top of the wing than at the bottom. The increase in velocity produces a decrease in pressure on top of the wing, so that there is an overall thrust upwards on the wing. Wind blowing across the top of a chimney can decrease the pressure in the chimney and cause it to 'draw' more effectively. Strong winds blowing around buildings can sometimes lower pressures enough to cause windows to blow outwards; this can be explained by reference to the Bernoulli's principle.

The Bernoulli's principle is also the basis of many devices that are used to measure the flow of liquid in rivers, channels, water mains and sewers.

Venturimeter

The venturimeter is a device which measures the flow rate in a pipe by applying Bernoulli's principle to the pressures measured in the pipe. A constriction is constructed in the pipe and pressure gauges are fitted in the pipe and in the throat of the constriction, as shown in figure 12.10. The liquid flowing in the reduced cross-section increases in velocity and therefore, by Bernoulli's principle, it has a lower pressure. The pressure heads in the pipe and the throat are measured and used to find the flow rate.

The flow rate or discharge varies in direct proportion to the difference in pressures measured by the meter. A direct reading of flow rate can be made

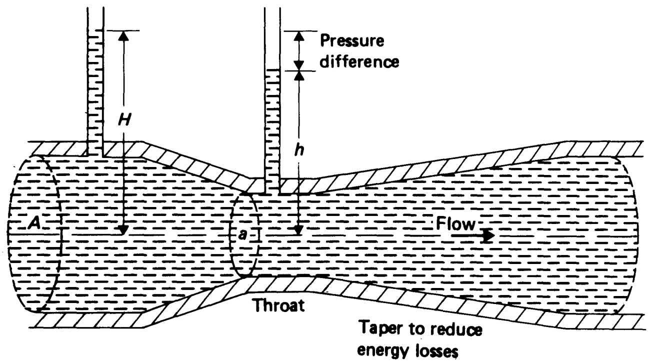


FIGURE 12.10 *Venturimeter*

from a suitably calibrated gauge, or else the flow rate can be calculated from the following formula.

$$Q = C_d A a \sqrt{\left(\frac{2g(H-h)}{A^2 - a^2}\right)}$$

where

Q = flow rate in the pipe (m^3/s)

A = cross-sectional area of pipe (m^2)

a = cross-sectional area of throat (m^2)

H = pressure head in pipe (m)

h = pressure head in throat (m)

g = gravitational acceleration = 9.81 m/s^2

C_d = the discharge coefficient for a particular meter (usually 0.98)

Venturimeters are commonly used in water mains and the loss of energy that occurs in the meter is minimised by using a long taper downstream from the throat of the meter.

Energy losses

According to Bernoulli's Theorem the total energy of the liquid flowing in a pipe is constant. In practice there is a continuous loss of energy, even in a horizontal pipe. *Friction* between the liquid and the pipe wall is the main cause of energy loss and the size of the resulting pressure drop depends upon the following factors:

1. roughness of the pipe wall;
2. area of the pipe wall;
3. length of the pipe;
4. velocity of flow;
5. turbulence of flow;
6. viscosity and temperature of the liquid.

The combination of these factors makes the theory of the pressure loss very complicated. In order to predict the pressure losses that can be expected in a given pipeline or channel, engineers use a number of practical formulas which have been found to give reasonable results in different situations.

A general relationship that arises from theory and practice is that the pressure losses in a pipe are proportional to the square of the velocity of the liquid

$$H \propto v^2 \quad \text{or, re-arranging terms} \quad v \propto \sqrt{H}$$

That is, the velocity of the flow is proportional to the square root of the pressure. So that, for example, when the pressure applied to a pipeline is doubled the velocity does not double but increases by the lesser factor of $\sqrt{2} = 1.14$.

Flow in pipes

A water mains is an example of liquid flowing in a full pipe. Friction energy losses in the pipe cause the pressure to drop when the liquid flows, as shown in figure 12.11. To maintain the flow it is necessary to replace the energy with energy from pumps. To design a pumping system the pressure losses that will occur in the pipeline need to be predicted.

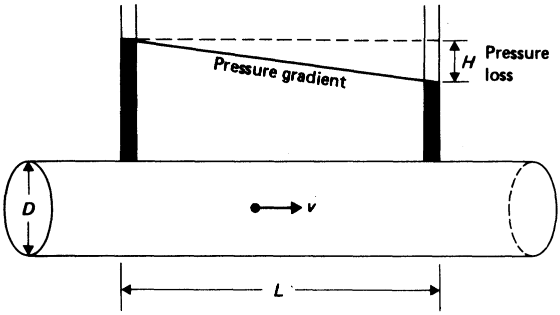


FIGURE 12.11 *Flow in full pipe*

Darcy's Formula Darcy's formula is one of the formulas that is used for predicting the pressure head lost from a liquid flowing in a *full* pipe because of friction between the liquid and the pipe surfaces

$$H = \frac{4fLv^2}{2gD}$$

where

H = loss of pressure head (m)

L = length of the pipe (m)

v = average velocity of flow in pipe (m/s)

D = internal diameter of pipe (m)

g = gravitational acceleration = 9.81 m/s^2

f = Darcy's frictional coefficient (dimensionless – no units)
The value of f is found in tables and ranges from about 0.005 for smooth pipes to 0.01 for rough pipes. The value of f is also different for laminar and turbulent flow

Flow in open channels

Water flowing in culverts, gutters and drain pipes are examples of liquid flowing in open channels or partly filled pipes. To maintain the flow in the channel the energy lost by friction is replaced by the potential energy of the liquid. The liquid must therefore always flow downhill under gravity and its total pressure head decreases as it flows.

Chézy Formula The Chézy formula expresses the relationship between the fall in height of a channel and the velocity of flow that this produces, as indicated in figure 12.12

$$v = c\sqrt{(mi)}$$

where

v = average velocity of flow (m/s)

m = hydraulic mean radius: $m = \dfrac{\text{cross-section area of flow (m}^2\text{)}}{\text{wetted perimeter (m)}}$

i = hydraulic gradient: $i = \dfrac{\text{loss of pressure head H (m)}}{\text{horizontal length of flow } L \text{ (m)}}$

c = Chézy coefficient for a particular pipe (for example, $c = 50\ \text{m}^{1/2}/\text{s}$)

The Chézy formula assumes that the channel is of uniform cross-section and roughness, with a constant gradient.

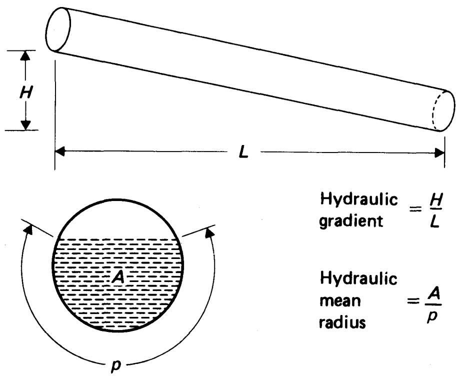


FIGURE 12.12 *Flow in open channel*

NATURAL WATERS

The world possesses a fixed amount of water, which is found to occur naturally in various forms, such as oceans, lakes, rivers, underground waters, ice caps, glaciers and rain. This water plays an important part in maintaining the balance of the world's weather, especially through the presence of water vapour in the atmosphere. Water is also essential for the growth of vegetation such as trees and food crops.

Man needs a small amount of water for drinking but much greater amounts are used for washing and waste disposal, in homes, industry and commerce. The daily consumption of water in some cities is over 300 l per person on average. The total supply of natural water in the Earth is enormous and should be adequate for man's needs. However, local shortages do occur especially when droughts are combined with poor management of resources. This section looks at the sources of water which are usually used for water supplies and describes the qualities that can be expected.

The hydrological cycle

A certain proportion of the world's natural water is involved in a continuous cycle of rainfall and evaporation. This hydrological water cycle, illustrated in figure 12.13, is made up of the stages now described:

(1) *Evaporation* When the Sun shines upon the surface of water, such as the oceans, some of the water evaporates from the liquid state to water vapour. The Sun also warms this water vapour which, becoming less dense than the cold air above it, rises into the atmosphere where it is circulated by weather patterns.
(2) *Condensation* When the water vapour becomes cooled below its dew point it condenses and the liquid water appears as clouds of droplets.
(3) *Precipitation* When the water droplets in a cloud are large enough they fall as rain, snow or hail.
(4) *Run off* A proportion of the precipitated water falls on the land where most of it flows towards the sea by two main routes – as surface water such as streams and rivers, and as groundwater which percolates through the materials below the surface of the land.

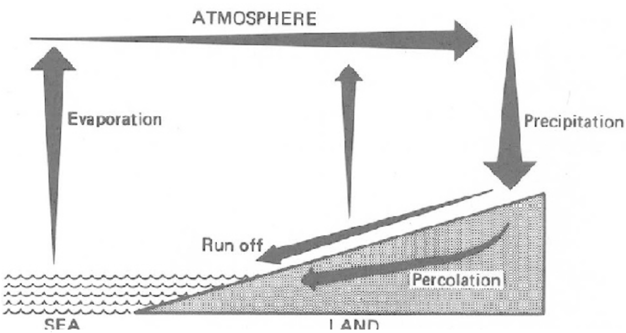


FIGURE 12.13 *Water cycle*

Plants participate in the hydrological cycle by absorbing moisture for the processes of their growth and by emitting water vapour in the process of transpiration. The energy for the hydrological cycle is provided by the Sun which supplies the latent heat for evaporation and then raises huge masses of water upwards against gravity. The many components and mechanisms of the cycle are interdependent on one another and achieve a complex natural balance which could, perhaps, be upset by major changes in some parts of the cycle.

Chemical terms

Names of Compounds Some references identify chemicals by their common names, or by out-dated chemical names. Table 12.1 lists equivalent names for some of the substances which are commonly referred to in descriptions of water supplies.

TABLE 12.1 *Chemical names*

Chemical name	Chemical formula	Other names
Aluminium sulphate	$Al_2(SO_4)_3$	alum
Calcium carbonate	$CaCO_3$	chalk, limestone
Calcium hydroxide	$Ca(OH)_2$	lime (slaked, hydrated)
Calcium hydrogen carbonate	$Ca(HCO_3)_2$	calcium bicarbonate
Calcium sulphate	$CaSO_4$	gypsum
Magnesium hydrogen carbonate	$Mg(HCO_3)_2$	magnesium bicarbonate
Magnesium sulphate	$MgSO_4$	epsom salt
Sodium carbonate	Na_2CO_3	soda
Sodium chloride	$NaCl$	common salt, brine
Sodium hydrogen carbonate	$NaHCO_3$	sodium bicarbonate

Acids and Alkalis An *acid* is a substance that contains hydrogen which can be chemically replaced by other elements. Acids have the ability to produce hydrogen ions, H^+.

An *alkali* or *base* is a substance which neutralises an acid by accepting hydrogen ions from it.

Both acids and alkalis are corrosive and dangerous when they are very strong, but many substances are weakly acidic or alkaline when they are dissolved in water.

pH Value The pH value is a measure of the acidity or alkalinity of a solution, rated on a scale that is related to the concentration of the hydrogen ions present

pH less than 7 – indicates an acid.
pH greater than 7 – indicates an alkali.

The pH value of a sample can be found by chemical measurements, or by using specially calibrated electrical meters which detect the number of H^+ ions present.

Characteristics of natural water

Pure water has no colour, no taste or smell, and is neither acidic or alkaline. Water can dissolve many substances and is sometimes termed a 'universal solvent'. Natural water is rarely chemically pure; even rainwater dissolves carbon dioxide as it falls through the air. Water which flows over the surface of the land or through the ground comes into contact with many substances and takes some of these substances into solution or into suspension.

The impurities and qualities that may be found in natural waters can be conveniently described under the following headings.

Inorganic Matter Dissolved inorganic chemicals, such as salts of calcium, magnesium, and sodium cause the hardness in water, which is discussed in a later section.

Suspended inorganic matter includes minute particles of sand and chalk, which do not dissolve in water. The particles are small enough to be evenly dispersed as a suspension which affects the colour and clarity of the water. A characteristic of a suspension is that it can be separated by settlement of the particles.

Organic Matter Dissolved organic materials usually have animal or vegetable origins and the products of their decay include ammonia compounds.

Suspended organic matter can be minute particles of vegetable or animal origin such as fibres, fungi, hair and scales.

Micro-Organisms Diseases in man are caused by small organisms such as certain bacteria, viruses and parasites. Some of these organisms can be carried by water if a supply is allowed to become contaminated. Examples include typhoid, cholera and dysentery.

Pollutants Human activities add extra impurities to natural water, mainly in the form of waste from sewage systems and from industrial processes. Domestic sewage carries disease organisms which must not be allowed to contaminate water supplies. The detergent content of household sewage can also be high and difficult to remove.

Industrial wastes, which can contaminate water supplies, include toxic compounds containing cyanide, lead, and mercury. Increased agricultural use of nitrogenous fertilisers, which are washed from fields, can lead to excessive nitrate compounds in the water supply. Certain levels of nitrates are thought to be a health hazard to young children.

Acidity Pure water is chemically pure, with a pH of 7, but natural water is invariably acidic or alkaline with an approximate pH range of 5.5 to 8.5.

Acidity in natural water is usually caused by dissolved carbon dioxide and dissolved organic substances such as peat. Acidic waters are corrosive and also dissolve lead, a poison, into the water from lead pipes.

Alkalinity in natural water is more common than acidity. It is usually caused by the presence of hydrogen carbonates.

Hardness

Some natural water contains substances which form a curdy precipitate or scum with soap. No lather forms until enough soap has first been used in the reaction with the substances producing this 'hardness'.

HARD WATER is water in which it is difficult to obtain a lather with soap.

UNIT: milligrammes per litre (mg/litre) of calcium carbonate ($CaCO_3$) irrespective of actual salts present.
Other units: 1 part per million (ppm) is approximately 1 mg/l; 1 'degree Clarke' is approximately 1 part per 70 000.

Typical Values of Hardness

0–50 mg/litre is termed *soft* water

100–150 mg/litre is termed *slightly hard* water

200 + mg/litre is termed *hard* water

About 40 per cent of the public water supply in the United Kingdom is between 200 and 300 mg/litre. In general, hard water comes from underground sources or from surface water collected over ground containing soluble salts such as carbonates and sulphates; for example in limestone areas. Soft water tends to come from surface water collected over impermeable ground, such as in granite areas.

Types of Hardness There are two main types of hardness of water, as now defined. The different types of hardness are particularly relevant for the processes of softening water which are described in a later section.

TEMPORARY HARDNESS is hardness that can be removed by boiling.

Temporary hardness is usually caused by the presence in the water of the following salts

$CaCO_3$ – calcium carbonate

$MgCO_3$ – magnesium carbonate

The scale or 'fur' found inside kettles is the by-product of removing temporary hardness by boiling.

PERMANENT HARDNESS is hardness in water which cannot be removed by boiling.

Methods of removing permanent hardness are described later in the chapter. Permanent hardness is usually caused by the presence of the following salts

$CaSO_4$ – calcium sulphate

$MgSO_4$ – magnesium sulphate

$CaCl_2$ – calcium chloride

$MgCl_2$ – magnesium chloride

Consequences of Hardness Hardness in water has the advantages and the disadvantages listed below. Public water supplies are not usually treated for hardness and the suitability of an untreated supply needs to be assessed for each application of the water.

Disadvantages of Hard Water

1. Wastage of fuel occurs because of scale in boilers and pipes.
2. Deterioration of boilers and pipes is caused by the scale.
3. Wastage of soap and energy occurs before a lather forms.
4. Increased wear occurs in textiles which have to be washed for longer periods.
5. Industrial processes are affected by the chemicals in hard water.
6. The preparation of food and drinks can be affected by hard water.

Advantages of Hard Water

1. Lesser amounts of toxic lead in pipes are dissolved by hard water.
2. 'Better taste' is usually a feature of hard water.
3. Decreased incidence of heart disease appears to be associated with hard water.

Sources of water supply

Rainfall is the original source of the water used for drinking. Part of the water evaporates from the Earth soon after it falls as rain; part of the water drains on the surface to join streams and rivers; and part of the water percolates into the ground to feed underground supplies. The balance of evaporation, surface water, and underground water varies with the particular climate, the district and the time of year. An average proportion is one third evaporation, one third run-off, and one third soak-in. A larger proportion of the rainwater is lost by evaporation during the summer.

Sources of water supply are usually classified by the routes that water has taken after rainfall. For supplies of drinking water the main categories are listed below and are described in the sections that follow:

1. *Surface water* Examples: streams, rivers, lakes and reservoirs.
2. *Underground water* Examples: springs and wells.
3. *Rainwater collectors* Examples: roofs and paved surfaces.

Underground water

When rain falls on soils or porous rocks, such as limestone or sandstone, some of the water sinks into the ground. When this water reaches a lower layer of impervious material, such as clay or rock, it may be held in a depression or it may flow along the top of the impermeable layer. Such water-bearing layers are called *aquifers*, and a cross-section of one is shown in figure 12.14. The water table or 'plane of saturation' is the natural level of the underground water. The water in some aquifers is 'confined' and held below the water table by an impermeable layer on top of the water.

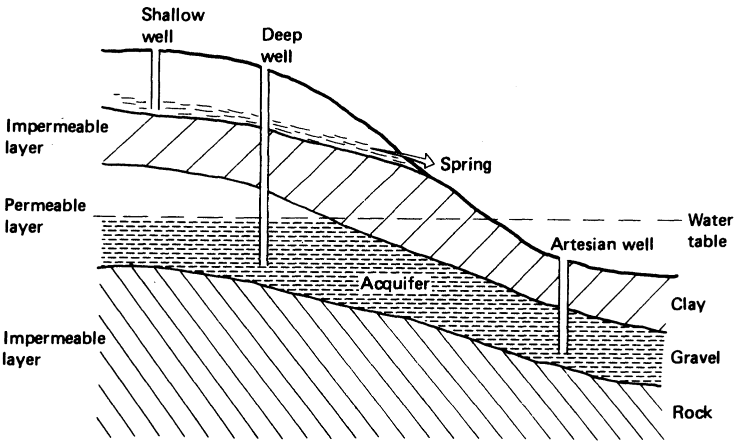


FIGURE 12.14 *Underground water supplies*

Springs A spring is a source of ground water that occurs when geological conditions cause the water to emerge naturally, as shown in figure 12.14. A simple land spring is fed by the surface water which has soaked into the sub-soil and its flow is likely to be intermittent. A main artesian spring taps water that has been flowing in an aquifer below the first impermeable layer. The water from such a spring is usually hard with a high standard of purity achieved because of the natural purification which occurs during the percolation through the ground. All springs need protection from contamination at their point of emergence.

Wells Wells are a source of underground water but, unlike springs, the water must be artificially tapped by boring down to the supply. Wells may be classified by the types listed below and shown in figure 12.14:

1. *Shallow wells* These tap water near the surface.
2. *Deep wells* These obtain water below the level of the first impermeable layer.
3. *Artesian wells* These deliver water under their own heads of pressure, because the plane of saturation is above the ground level.

The classification of wells as shallow or deep depends on where they take water from and not upon the depth of their bore. Shallow wells may give good water but there is a risk of pollution from sources such as local cesspools, leaking drains and farmyards. Deep wells usually yield hard water of high purity. The construction of all wells must include measures to prevent contamination near the surface.

Surface water

Water collected in upland areas tends to be soft and of good quality, except for possible contamination by vegetation. As a stream or river flows along its course it receives drainage from farms, roads and towns and becomes progressively less pure. Many rivers receive sewage and industrial waste from towns and factories and are also required to supply fresh water to other towns. It is obviously important that the levels of pollution in rivers are controlled and experience has shown that even rivers flowing through areas of heavy industry can be kept clean if they are managed correctly.

A flowing river tends to purify itself, especially if the flow is brisk and shallow. This self-purification is due to a combination of factors including oxidation of impurities, sedimentation of suspended material, the action of sunlight and dilution with cleaner water. Even so, water taken from a river for use in a large public supply usually needs treatment on a large scale. Such water must also be carefully analysed for its chemical and bacteriological content.

WATER TREATMENT

The variety of types and qualities of natural waters described in the previous section indicates that there are a wide range of substances whose concentrations may need to be adjusted before a water is used. The water for a public water supply is required to be 'wholesome', meaning that it is suitable for drinking. Good drinking water can be described as water which is harmless to health, colourless, clear, sparkling, pleasant tasting and odourless.

Methods of treatment

The principal techniques used for water treatment are described in following sections and can be summarised under the general headings given below:

1. *Storage* sedimentation and clarification.
2. *Filtration* slow sand filters, rapid sand filters and micro-strainers.
3. *Disinfection* chlorination and ozonisation.

The methods used for the treatment of a particular water depend upon whether it is in small supplies or bulk supplies, and whether it is needed for domestic or industrial use. The components of a typical water treatment works are shown in figure 12.15. Many industrial processes require water with less mineral content than is acceptable for drinking water and further treatment stages, such as softening, are then necessary.

Storage

Reservoirs are used to store reserves of water and they are also an important preliminary stage of treatment. All contaminants in the water are diluted in

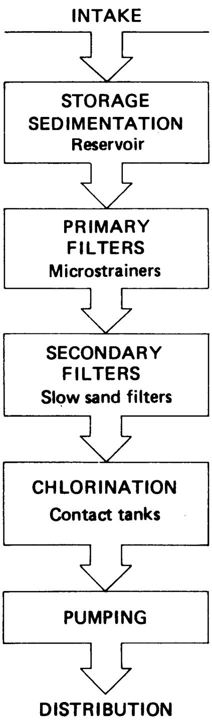


FIGURE 12.15 *Water treatment scheme*

their effect and different qualities of water are evened out. Pathogenic (disease-producing) bacteria tend to die when in storage because of lack of suitable food, the low temperature and the action of sunlight.

A disadvantage of prolonged storage of raw water is that it provides conditions for the growth of algae: minute plants that make subsequent water treatment difficult. Algae can be controlled by the careful addition of chemicals, such as copper sulphate, and by the mixing of water in a reservoir system.

Sedimentation is the gradual sinking of impurities that are suspended in the water. Simple sedimentation – the natural settling of suspended materials – takes place in reservoirs and also in specially designed settling tanks.

Clarification is a system of chemically assisted sedimentation used for the removal of very fine suspended particles which do not settle naturally. A chemical such as aluminium sulphate ('alum') produces a precipitate when it is added to the water. This precipitate coagulates with the suspended material to form a *floc*. This product of 'flocculation' then settles as a sediment, or it may be removed by mechanical collectors.

Filtration

When water is passed through a fine material, such as sand or a wire mesh, particles are removed from the water. Some filters, such as rapid sand filters, act only as a simple physical filter and the water also requires chemical treatment. Slow sand filters however, combine a physical action with a chemical and a bacteriological action.

Slow Sand Filters Slow sand filters are built in sunken rectangular basins; 100 m x 40 m being a typical size. A cross-section of a modern slow sand filter is shown in figure 12.16. The floor of the filter bed contains a system of collector pipes and underdrains covered with a layer of graded gravel. Above the gravel is a layer of sand, about 600 mm deep, which is then covered with water to a depth of around one meter.

Water slowly percolates downwards through the sand bed which develops a film of fine particles, micro-organisms, and microscopic plant life. It is this complex 'vital' layer which purifies the water by both physical and biological action. Because the growth of the active film reduces the rate of filtration the head of water is gradually increased until, after a period of weeks, the bed has to be emptied for cleaning. The top 12 to 25 mm of sand is removed, washed and eventually used for replenishing the beds. A clean filter is 'charged' by slowly filling it with water from the bottom upwards and then allowing a new vital layer to form.

The slow sand filter is extremely effective and gives high quality water, which needs little further treatment. The filters occupy larger areas and work more slowly than other types of filter. The mechanical scraping and the cleaning of the sand has been made quicker and less labour-intensive by the use of machines.

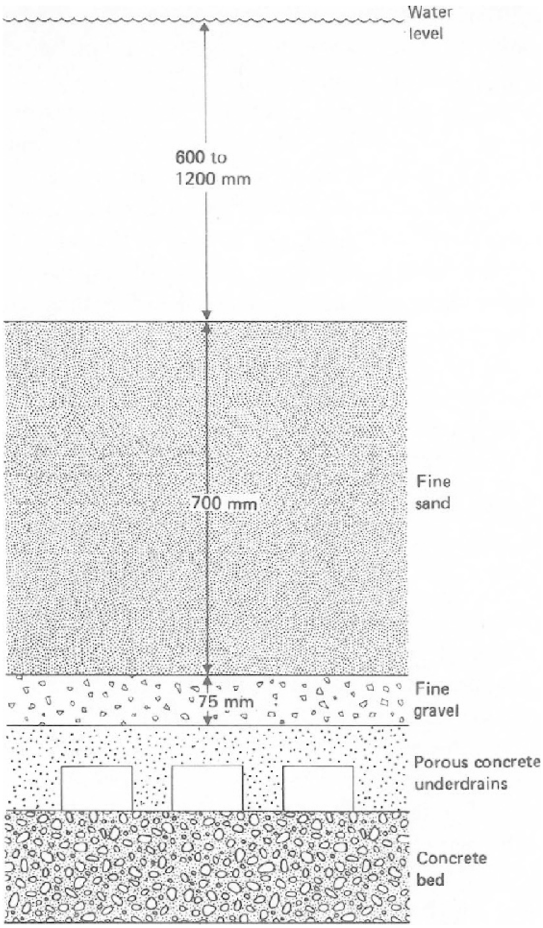


FIGURE 12.16 *Slow sand filter*

Rapid Gravity Filters Rapid gravity sand filters are constructed in tanks which have dimensions up to 12 m by 9 m. A uniform bed of sand, about 600 mm thick is supported on a bed of gravel of similar thickness. Beneath the gravel is a system for collecting water and also for passing air and water upwards. The filter is filled with water to a depth of 2 to 3 m.

The water passes downwards through the sand and the filtration is mainly by physical action. The filters are cleaned by draining and then blowing a strong scour of air followed by a backwash of clean water from below. Washouts are required at intervals of 12 to 48 hours but the procedure can be automated.

Rapid gravity filters work at a rate which is some 20 to 40 times faster than slow sand filters. Their construction is more compact than slow filters and they can be cheaper to install and to operate. A rapid gravity filter is much less effective than a slow sand filter and a rapid filter is usually used in conjunction with flocculated water. Rapid filters are also used as 'primary filters' which reduce the load on the slow sand filters which follow them.

Pressure Filters Pressure filters are contained in steel pressure vessels. The construction of the sand filter inside the vessel is similar to the open rapid gravity filters and the backwashing is carried out in a similar way. The whole of the pressure cylinder is kept filled with water so that pressure is not lost during filtration and this type of filter can be inserted anywhere in a water main.

Micro-strainers Micro-strainers are revolving drums with a very fine mesh of stainless steel wire or other material which is cleaned by water jets. The strainers are useful for screening stored waters which do not contain large amounts of suspended matter. By removing microscopic-sized particles of algae they can decrease the load on sand filters. Sometimes micro-strainers can produce water pure enough for sterilisation, without the need for filtration.

Disinfection

The disinfection of water supplies is intended to reduce harmful organisms, such as bacteria, to such very low levels that they are harmless. This safe quality needs to be maintained while the water is in the distribution system, including any reservoirs which store purified water. Disinfection can be achieved by a number of agents but chlorine and ozone are usually employed to treat public water supplies.

Chlorination Chlorine is a powerful oxidising agent which attacks many organic compounds and has the property of killing bacterial cells. The rate of disinfection of a particular type of water depends upon the chemical form of the chlorine and on the length of time it is in contact with the water. The presence of ammonia in the water reduces the effectiveness of the chlorine, but the addition of ammonia after disinfection can be useful for reducing possible objectionable tastes produced by the chlorine.

The chlorine is usually kept liquefied in tanks from where it is injected into the water at a controlled rate. Because the sterilising effect is not instantaneous the water and the chlorine are held in *contact tanks* for a period of time, such as 30 minutes.

Ozone Treatment Ozone, O_3, is a form of oxygen with molecules that contain an extra atom. This form is very unstable and ozone is a powerful oxidising agent which rapidly sterilises water. Ozone treatment is more expensive than chlorination as the ozone must be made at the treatment station. Air is dried, subjected to a high voltage electric discharge and the ozone produced is then injected into the water.

Softening of water

Hard water is satisfactory, and even desirable, for drinking but hard water also has disadvantages which were described previously. It is not usual practice to soften public supplies of water but softening may be necessary for industrial supplies. There are several different methods used for changing hard water into soft water:

Precipitation methods act by completely removing most of the hardness compounds which are present in the water. Chemicals are added to the hard water to form insoluble precipitates which can then be removed by sedimentation and filtration.

Base exchange methods act by changing hardness compounds into other compounds which do not cause hardness.

Demineralisation is the complete removal of all chemicals dissolved in the water. This can be achieved by an ion-exchange which is a more complete process than the base-exchange.

Lime–Soda Treatment 'Lime' and 'soda' processes are precipitation methods of water softening. They depend upon chemical reactions to make the calcium and magnesium content of the hard water become insoluble precipitates which can then be removed. The following softening reactions use the chemical terms listed in table 12.1.

Calcium temporary hardness is treated by *lime*

$$\underset{}{Ca(HCO_3)_2} + \underset{\text{slaked lime}}{Ca(OH)_2} \longrightarrow \underset{\text{precipitate}}{2CaCO_3} + 2H_2O$$

Calcium permanent hardness is treated by *soda*

$$CaSO_4 + Na_2CO_3 \longrightarrow CaCO_3 + Na_2SO_4$$

or

$$CaCl_2 + \underset{\text{soda ash}}{Na_2CO_3} \longrightarrow \underset{\text{precipitate}}{CaCO_3} + 2NaCl$$

Magnesium temporary hardness is treated by *lime*

$$Mg(HCO_3)_2 + \underset{\text{slaked lime}}{2Ca(OH)_2} \longrightarrow \underset{\text{precipitate}}{2CaCO_3} + Mg(OH)_2 + 2H_2O$$

Magnesium permanent hardness is treated with *lime* and *soda*

$$MgSO_4 + Ca(OH)_2 \longrightarrow Mg(OH)_2 + CaSO_4$$

or

$$MgCl_2 + Ca(OH)_2 \longrightarrow Mg(OH)_2 + CaCl_2$$

slaked lime — treat as for calcium

In a lime–soda softening plant the chemicals are measured and added to the water, either dry or in a slurry. The solids formed in the precipitation are removed by settlement in tanks, or by flocculation, and the water is then filtered. Lime–soda water softening processes have relatively low running costs but produce large quantities of sludge which require disposal.

Base-Exchange Method In the base-exchange method of water softening the hardness-forming calcium and magnesium salts are converted to sodium salts which do not cause hardness. *Zeolites* are the special materials which act as a medium for the exchange of ions

calcium sulphate (hard) + sodium zeolite ⟶ calcium zeolite + sodium sulphate (soft)

The exhausted zeolite is 'regenerated' with sodium from a salt solution

calcium zeolite + sodium chloride ⟶ sodium zeolite + calcium chloride

Natural zeolites are obtained from processed sands and synthetic zeolites are made from organic resins such as those of polystyrene. The water softener is usually a metal cylinder, constructed like a pressure filter, in which the water passes downwards through a bed of zeolite. When regeneration is necessary dilute brine is passed through the bed, followed by a freshwater wash.

The base-exchange process can be operated simply and automatically but its costs depend upon the availability of salt. The process is used for commercial supplies such as for boilers and laundries and for household water softeners.

EXERCISES

1 When an oil-filled manometer measures a certain pressure the difference in oil levels is 240 mm. Express this pressure as an absolute pressure. Given: density of the oil is 830 kg/m^3: gravitational acceleration is 9.81 m/s^2.

2 A reservoir dam, 200 m in length, has a vertical face which retains water to a depth of 15 m. Calculate the horizontal force on the dam produced by the

retained water. Given: density of water is 1000 kg/m^3; gravitational acceleration is 9.81 m/s^2.

3 A 200 mm dia. pipe runs into a 150 mm dia. pipe with a discharge rate of 0.04 m^3/s. If both pipes are running full bore calculate the flow velocities in each pipe.

4 A venturi meter has a throat of 80 mm dia. and is set in a horizontal water main of 150 mm dia. If the measured pressure heads are 13.7 m in the main and 10.5 m in the throat calculate the flow rate in the pipe. Given: discharge coefficient for the meter is 0.98; gravitational acceleration is 9.81 m/s^2.

5 A 100 mm dia. water main is required to discharge at 0.035 m^3/s when running full bore. Calculate the loss of pressure head that occurs in a 150 m horizontal run of this pipe. Use Darcy's formula and assume a friction coefficient of 0.006 for the pipe.

6 A circular drain of 150 mm dia. is laid with a fall of 1 in 40. If the drain runs half full then use the Chézy formula to calculate:
(a) the flow velocity in the drain and;
(b) the discharge rate.
Assume a Chézy coefficient of 50 $m^{1/2}/s$.

ANSWERS

1 1954 Pa
2 220.7 MN
3 1.273 m/s, 2.264 m/s
4 0.041 m^3/s
5 36.43 m
6 1.531 m/s, 0.0135 m^3/s

Conclusion

A building should provide a suitable environment for people or for equipment. In order to create safe, comfortable and pleasant conditions the structure and services of the building need to provide protection from the environment outside and to modify the environment inside. The basic human needs are for air, warmth and light; but other factors such as noise, glare, dirt, space and privacy also affect the human sense of comfort.

The following considerations are among the design factors that affect the final environment of a building:

1. position of the building on its site;
2. basic shape and area of the building;
3. thermal insulation and thermal response of building materials;
4. extent and type of windows;
5. nature of ventilation;
6. temperature and humidity of air;
7. artificial light qualities;
8. natural light qualities;
9. sound insulation of the construction;
10. acoustic qualities of interior.

Although the various topics that make up environmental technology are defined separately it is important to appreciate their interdependence when they are combined together in a building. All of the environmental factors have ideal standards to be separately satisfied but they may also need to be balanced against one another. As a simple example, larger windows provide better daylighting but they also cause greater heat losses in winter and larger heat gains in summer. The accompanying table of environmental factors indicates some of the major interactions between different design decisions.

The topics studied as environmental science are not only an essential consideration in building design, they must also be considered together and at an early stage in the design. The need for this integrated and early involvement of environmental studies has often been neglected. Historically, engineers have specialised in one particular aspect of controlling the environment of a building and have not considered the effects of their decisions on other areas of the environment. As a result, many modern buildings are environmental failures, despite the improved technology available. To provide the best possible

TABLE C.1 *Interactions of environmental decisions*

Some design options	Possible environmental effects			
	Heating	Ventilation	Lighting	Sound
Sheltered site	Less heat loss and gain		Less daylight	Less noise intrusion
Deeper building shape	Less heat loss and gain	Reduced natural ventilation	Less daylight	
Narrower shape	Greater heat loss and gain	Increased natural ventilation	More daylight	More noise intrusion
Heavier building materials	Slower heating and cooling			Greater sound insulation
Increased window area	Greater heat loss and gain		More daylight	More noise intrusion
Smaller, sealed windows	Less heat loss and gain	Reduced natural ventilation	Less daylight	Less noise intrusion

environment in future buildings all available knowledge and skill needs to be integrated. Design teams, professional groups and teaching should be oriented towards such an integrated approach.

Integrated environmental design

Integrated Environmental Design (IED) is a philosophy and method of designing buildings which aims to achieve the optimum environmental decisions. Each discipline or specialisation expands its design perspectives so as to be involved in neighbouring disciplines and in the overall design. So, for example, the building services specialists should also be involved in other decisions such as those concerning shape, orientation, use of materials, fenestration, lighting and sound control.

An integrated approach to design has been found to produce better designs and can give quicker results at no additional cost. A basic requirement is for a competent design team who all have a good understanding of building methods, materials and environment. The performance standards expected of the building need to be defined as clearly as possible and regular contact maintained with the client throughout the design stage. The overall design needs to be optimised for acceptable initial and future costs as well as for environmental effects.

Useful References

The following publications include sources of authoritative reference and useful further reading:

British Standards. British Standards Institution.
British Standard Codes of Practice. British Standards Institution.
The Building Regulations. H.M.S.O.
Building Research Establishment (BRE) Digests. H.M.S.O.
CIBS Guide (formerly *IHVE*). Chartered Institution of Building Services.
CIBS Code for Interior Lighting (formerly *IES*). Chartered Institution of Building Services.
Department of the Environment Advisory Leaflets. H.M.S.O.

The standards and the technology of environmental science are always improving and some aspects of the subject are of topical interest. Appropriate professional and technical journals should be read as part of the continuing study of environmental science.

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